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ARCTEC CANADA LIMITED

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LABORATORY ICE SUPPRESSION EXPERIMENTS USING A CANNON BUBBLER

PREPARED FOR:

TRANSPORTATION DEVELOPMENT CENTRE,
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BY

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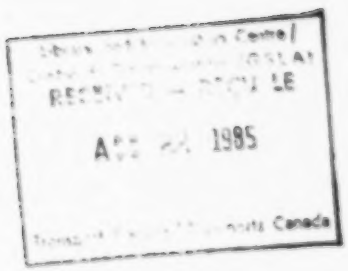

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17. Abstract

A series of laboratory experiments undertaken to assess the flow development and heat transfer capabilities of an air cannon flow developer is described. The tests included monitoring of air flow rates, water temperatures, ice thicknesses and water velocities. A range of temperature regimes and three bubbler types were used to compare relative effectiveness.

Test results are compared with numerical model results, and comparisons are also made of the three bubblers tested under different conditions. The cannon bubbler with deflector melted ice to a radius of 9 metres in a test where the air temperature was -5.2°C, water temperature of 0.60°C and air discharge of 75 standard cubic feet per minute. The cannon bubbler with the vertical discharge pipe and the hose (point source) bubbler melted less under similar conditions.

It was concluded that the full-scale air cannon bubbler with deflector will be more effective in suppressing natural ice cover than other types tested. Additional tests are recommended to assess the system under a variety of air flow rates. Installation of this system is recommended at Thunder Bay and at other ice-prone harbours.

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17. Résumé

Ce rapport décrit une série d'expérimentations en laboratoire visant à évaluer les courants et les flux thermiques induits par un mélangeur à canon pneumatique. Ces expérimentations ont englobé la mesure des débits d'air, de la température et de la vitesse d'écoulement de l'eau, ainsi que de l'épaisseur des glaces. Les chercheurs ont fait varier les températures et ont testé deux autres types de diffuseurs pour définir l'efficacité relative du système considéré.

Les résultats dérivés d'une modélisation numérique ont été confrontés aux résultats expérimentaux. Le rendement des trois types de diffuseurs éprouvés dans diverses conditions d'essai a également été comparé. Le canon pneumatique garni d'un déflecteur a provoqué la fonte des glaces dans un rayon de 9 mètres, la température ambiante étant de -5,2°C, celle de l'eau 0,60°C, et le débit d'air de 75 pieds cubes standard par minute. Dans des conditions identiques, le canon pneumatique sans déflecteur et le tuyau diffuseur souple (à décharge ponctuelle) se sont avérés moins efficaces.

En conclusion, le canon pneumatique à déflecteur est, de tous les types testés, celui qui, en vraie grandeur, donnera les meilleurs résultats. Le rapport préconise de nouveaux essais pour en évaluer le rendement sous divers régimes d'alimentation en air. Il recommande son implantation à Thunder Bay et dans d'autres bassins portuaires sujets à la formation des glaces.

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NOMENCLATURE

A_o	area of deflector outlet
A_p	area of bubbler pipe
b	function of diffusivity
C	coefficient
D	bubble diameter, diameter of pipe outlet, depth of diameter of the flow
g	acceleration due to gravity, gravitational constant
h	rate of heat transfer
N_u	Nusselt number
P	rotameter outlet pressure
P_r	Prandlt number
Q	discharge per unit area
Q_o	discharge at bubbler outlet
r	radius of bubble
R_e	Reynolds number
SCFM	standard cubic feet minute
SCFH	standard cubic feet hour
T	rotameter outlet temperature
U	mean horizontal velocity
U_B	rising velocity of air bubble
U_o	horizontal velocity from deflector outlet
α	efficiency factor
λ	scaling factor
π	3.14

1. INTRODUCTION

1. INTRODUCTION

1.1 Background

Transport Canada has commissioned a series of field experiments at Thunder Bay harbour to evaluate the use of air bubblers to induce early melting of ice in the harbour slips [1, 2, 3, 4, and 5]. Conventional bubblers were used initially, but proved excessively prone to damage during the shipping season. Cannon bubblers were less prone to damage since they can be built as part of the dock structure and be placed so as to avoid the ship traffic area.

The theory of bubbler operation suggests that cannon bubblers are more efficient at inducing vertical water currents than are conventional bubblers, and this was observed in early field trials. These trials also showed, however, that the area melted by the cannon bubblers was limited by their vertical orientation [6].

A modified version of the air cannon bubbler capable of inducing a horizontal or lateral flow was made. A series of tests was then conducted on a reduced scale version of this bubbler, to assess its horizontal flow development and ice melting capabilities prior to full-scale installation at Thunder Bay.

1.2 Theory of Operation

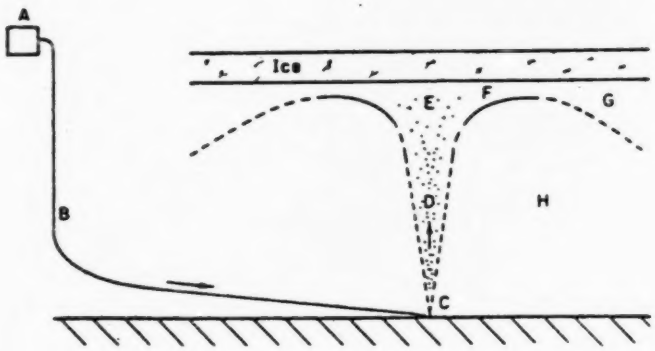
Ashton [7] modelled the water and heat transfer capability of conventional, point and line source bubblers. The main components of Ashton's model are illustrated in Figure 1.1.

A bubbler stream forms at the diffuser orifice (C). The bubbles rise and entrain surrounding water as they do so. The radius of the bubble plume expands approximately linearly with height, expanding the radius of entrained water (D). At the surface, the plume spreads laterally under the ice, creating a convection cell and eventually dispersing. Ashton's models describing the radius of vertical flow, centreline velocity of the plume and induced flow at the water surface are shown in Figures 1.2, 1.3 and 1.4.

Ashton's model was developed for conventional bubblers and not for air cannon bubblers. No tests have previously been conducted to our knowledge comparing the two types of bubblers, but theory suggests the air cannon bubbler will not follow Ashton's model since it acts as a flow developer.

The air cannon bubblers are expected to perform better than conventional bubblers described by Ashton's model for the following reasons:

- The velocity of the induced current under the ice cover is significantly larger for the cannon bubbler because it produces a larger confined bubble. According to Wegener and Parlange [8], the theoretical velocity of a rising air bubble is described as:



(AFTER ASHTON 7)

A -COMPRESSOR

B -AIR SUPPLY LINE

C -DIFFUSER LINE

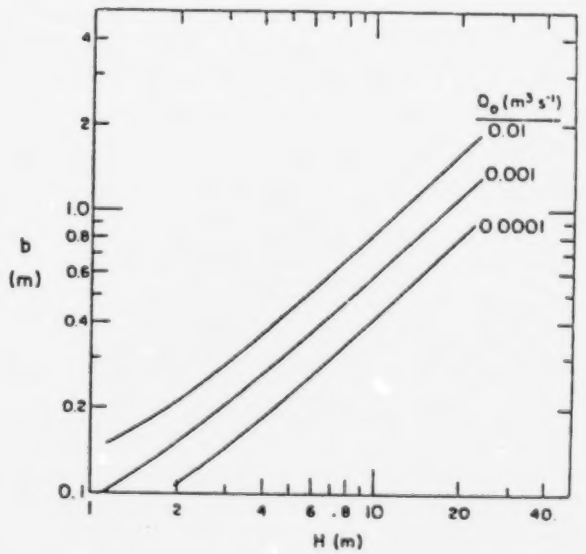
D -RISING PLUME OF ENTRAINED WATER

E -PLUME SPREADS UNDER ICE SURFACE

F -REGION OF HORIZONTAL FLOW OF PLUME

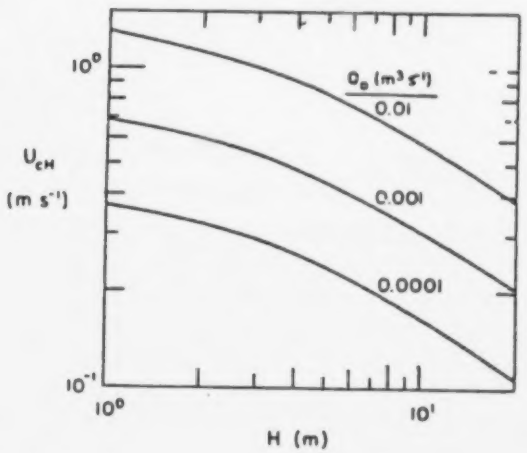
G -DISSIPATION OF ENTRAINED WATER

FIGURE 1.1 SCHEMATIC DIAGRAM OF CONVENTIONAL BUBBLER SYSTEM OPERATION



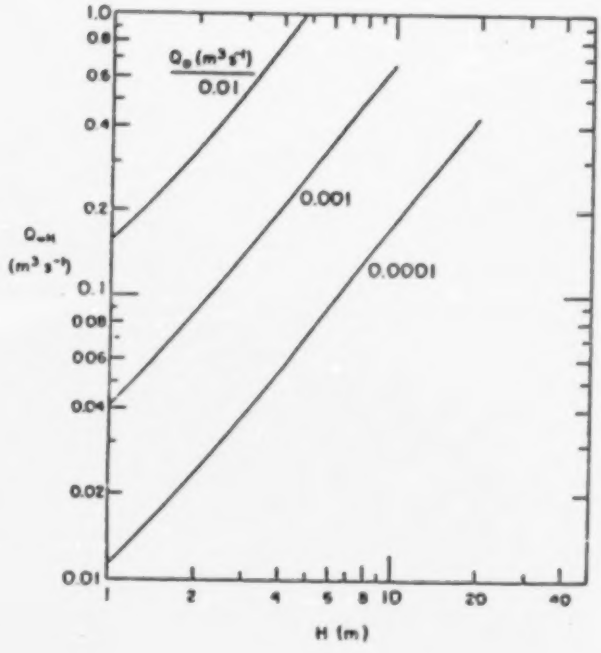
(after ASHTON 7)

FIGURE 1.2 **RADIUS OF INDUCED VERTICAL FLOW AT THE SURFACE FOR CONVENTIONAL BUBBLER**



(after ASHTON 7)

FIGURE 1.3 **CENTRELINE VELOCITY OF PLUME FOR CONVENTIONAL BUBBLER**



(after ASHTON 7)

FIGURE 1.4 INDUCED FLOW AT WATER SURFACE FOR CONVENTIONAL BUBBLER

$$U_B = \sqrt{gr} \qquad (1.1)$$

where U_B= the rising velocity of the air bubble,
g = acceleration due to gravity, and
r = the radius of the bubble.

Figure 1.5 compares the rising velocity for bubbles produced by the cannon and a single point bubbler. Velocity exceeds 1.5 m/s for the former and is less than .1 m/s for the latter.

- The efficiency of entrainment in a confined duct such as the cannon bubbler is greater than that from a point source bubbler. The manufacturer of the cannon bubbler states that entrained water velocity is 75 to 80% (depending on the ratio of the burper depth to the depth of the bubbler pipe inlet) of the rising bubble velocity. This velocity is dependent on the bubble size (See Figure 1.5) which for the cannon bubbler is 10 cm and for point source bubbler is less than 2.5 cm. Therefore the rising velocity of the bubble for the cannon bubbler is about 80% of 0.9 m/sec while for the point source bubbler is less than 70% of 0.4 m/sec.

- The higher currents generated by the cannon bubbler are used more efficiently in ice melting. Energy is lost when the rising plume of the point source bubbler impinges on the under surface of the ice. This reduces significantly the ability of the bubbles to entrain water in the horizontal direction. Where open water is present above the rising plume the loss of energy is even worse since the resulting waves are dissipated by gravity and blocked by the ice edge. Loss of energy from the rising plume is less severe for the cannon bubbler because the currents generated can be directed as required using a deflector.

- The higher current velocity generated by the cannon bubbler results in a higher Reynold's number and thus, in a higher coefficient of heat transfer, h. This is shown by Ashton [7] as:

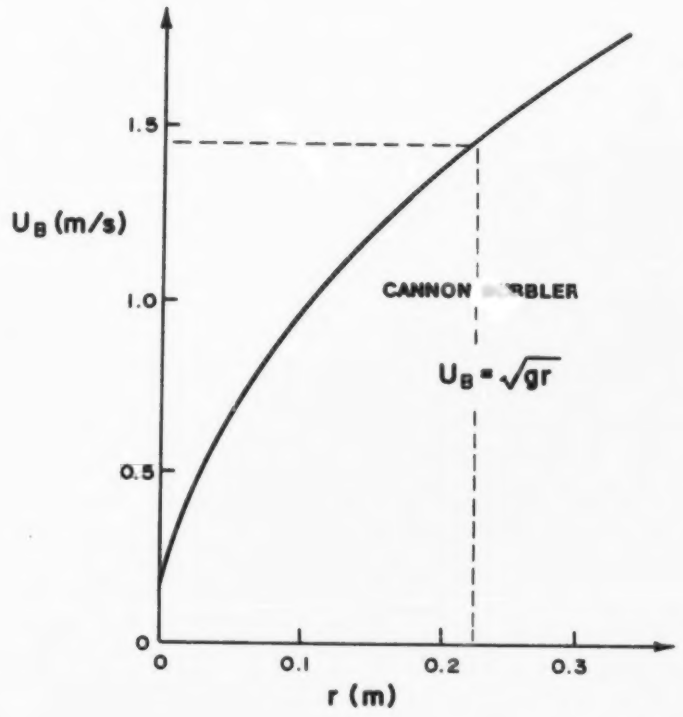
Average over the impinging area $h_b = 1920\ U_c^{0.62}/b^{-0.36}$ (1.2)

Radial decay $h_r = h_b/(v/b)^{-0.45}$ for $r > b_a$

where U_c is the final velocity of the rising plume
b is a function of the diffusivity versus distance from the centre of the impinging point of the water under the ice cover.

Since the diffusivity is expected to be smaller for the cannon bubbler, a higher heat transfer can be expected.

In conclusion, theory of bubbler operation strongly suggests that the air cannon mixer will perform better than conventional bubblers.



(after WEGENER and PARLANGE 8)

FIGURE 1.5 BUBBLE RADIUS AND RISING VELOCITY

2. OBJECTIVES

The objectives of this project were to evaluate the ice melting capacity of air cannon bubblers with and without heating jackets at laboratory scale. Further, air cannon performance at larger scale was to be predicted. The air cannon bubbler's ability to induce horizontal flow was to be examined in particular, as regards to ice melting capacity.

During the experiments, the heating jacket tests were done by using warmer water rather than adding heat to raise the water temperature.

3. METHOD OF APPROACH

3.1 Test Basin and Data Acquisition

All experiments were conducted in Arctec Canada's refrigerated testing basin. The dimensions and principal characteristics of the basin are shown in Table 3.1.

The basin's environment is controlled by a refrigeration system which can maintain temperatures as low as -20°C ± 2°C. For these tests, temperatures were controlled automatically by computer.

The work originally proposed involved a single ice sheet and one Atara bubbler. During the experiment this was expanded to four ice sheets and three types of bubblers, to allow comparison of a wider variety of conditions.

3.2 Test Parameters

The laboratory tests included measurement or control of the following parameters:

- bubbler outlet configuration
- bubbler air flow rate
- water velocity profile
- water temperature profile
- air temperature
- ice thickness and bubbler hole diameter

Three bubbler outlet configurations were used: air cannon bubbler with horizontal deflector; air cannon bubbler without deflector, and hose bubbler. Tests were conducted to compare the three bubbler types.

The bubbler air flow rate was controlled, and water velocity profile measured to test the efficiency of horizontal flow generation at different discharge rates. Water velocity controls the rate of heat transfer to the ice surface.

Water temperature was measured to calculate the heat transfer rate to the bottom of the ice cover.

Air temperature is related to heat loss to the atmosphere, and is an important control in bubbler effectiveness.

Finally, ice thickness and bubbler hole diameter are related to heat loss to the atmosphere, and of course are indicators of bubbler effectiveness in melting the ice cover.

Analytical relationships between the above parameters are described in the analysis section of this report (5.0), while methods of measurement are detailed below.

TABLE 3.1

TEST BASIN CHARACTERISTICS

TOWING BASINS	BASIN NO. 1 KANATA	
Basin		
Length	30.5m	100'
Width	4.9m	16'
Depth	1.5m	6'
Towing Carriage		
Drive System	5 HP	
Maximum Load	2.3 tons	
Speed Range	0.006-1.3m/sec	
Wavemaker	Electro-Mechanical	
Ice Preparation Method	Freezing with Liquid Nitrogen or Conventional Refrigeration Plant	
Ice Preparation Capability	6mm/hr	
Temperature during Preparation	to - 75°C	
Temperature during Testing	0 to -20°C	

3.3 Bubbler

Three types of bubblers were used during the tests; a cannon bubbler with vertical discharge pipe, a cannon bubbler with deflector attachment, and a hose (point source) bubbler. The cannon bubbler was manufactured by Atara Corporation and is illustrated in Figure 3.1. The cannon bubbler was equipped with an electric coil to heat the water in the bubbler tube, and with an air vent to allow bubbles to escape at the top. The heating coil proved inoperative after it was installed, and the heating jacket tests were therefore revised. Instead, water temperatures in the test basin were controlled. The hose bubbler consisted of a one half inch diameter hose with a single hole. The cannon bubbler was mounted on an underwater carriage as shown in Figure 3.2.

The principle of operation of an air bubbler is as follows: Air is supplied by a compressor and is injected into the water through an orifice (located at "bubble generator" in Figure 3.2). For the air cannon bubbler, the air bubble is accumulated to a critical level in the bubble generator, and ejected as a single, large bubble into the vertical stack. The bubble then acts as a piston to pump water out of the stack.

This approach concentrates the air/water flow, minimizing the loss of velocity in horizontal diffusion as the bubbles rise.

The bubbler discharge rate was controlled during the experiments by controlling air pressure at the orifice and was calculated as:

$$SCFM = \frac{SCFH}{60}\left[\left(\frac{14.7 + P}{14.7}\right)\left(\frac{530}{460 + T}\right)\right]^{\frac{1}{2}}$$

where SCFM = standard cubic feet per minute at 70°F, 14.7 psig
SCFH = indicated standard cubic feet per hour at rotameter
P = rotameter outlet pressure
T = rotameter outlet temperature

3.4 Temperature Measurement

Temperatures were measured using a Wheatstone bridge arrangement with linear thermistors, obtaining an accuracy of ± 0.15°C. Thermistors were mounted on a moveable rack which was placed in front of the cannon bubbler during each test. The horizontal and vertical location of each thermistor is indicated in the temperature profile plots in Appendix A.

3.5 Current Meter

A Marsh McBirney current meter was used to measure the currents at the depth of the harbour. On the water surface, water velocity was measured with a float and stop watch.

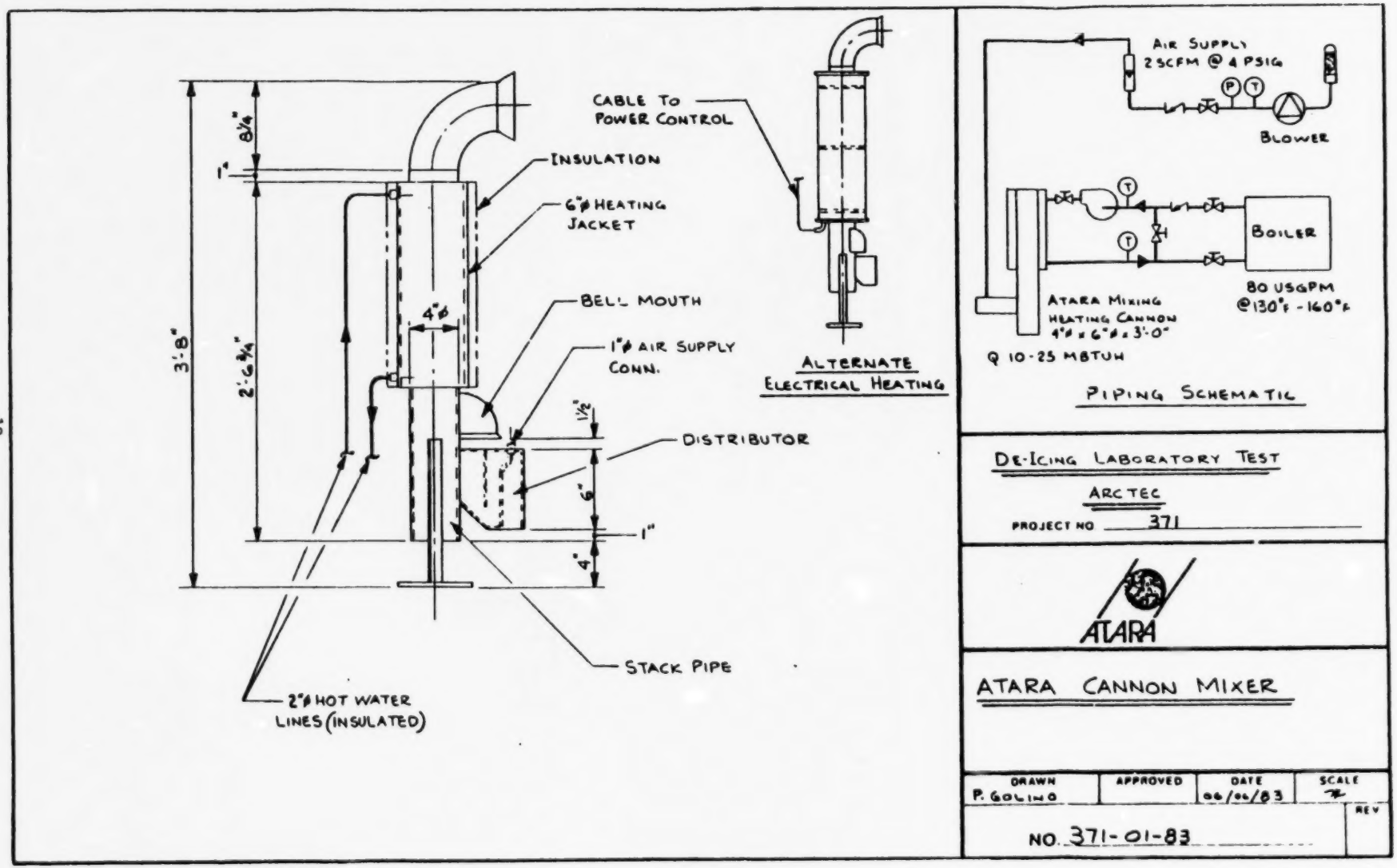


FIGURE 3.1 ATARA CANNON BUBBLER

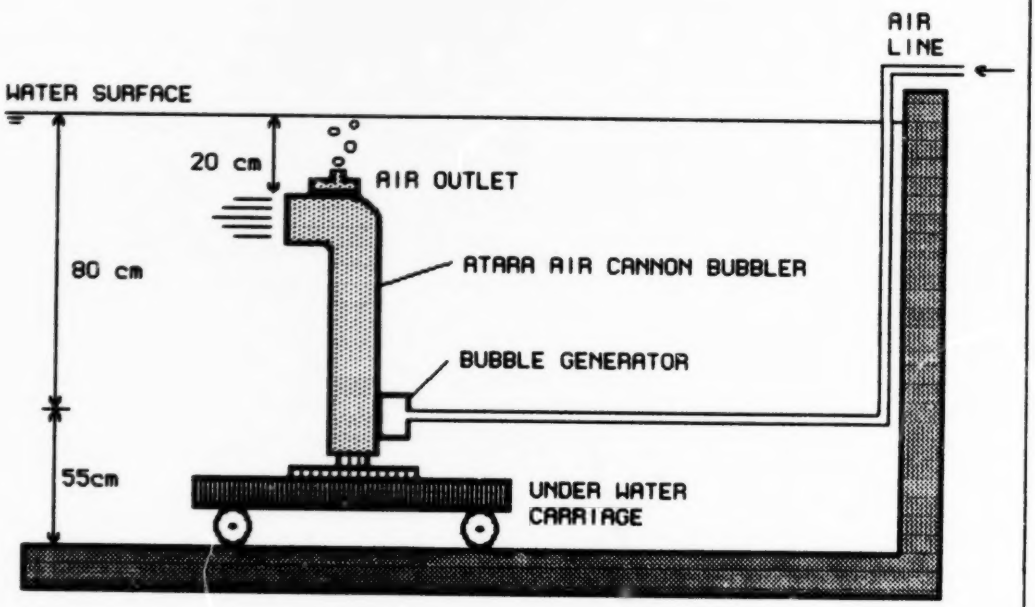


FIGURE 3.2 PROFILE OF TEST SET-UP

3.6 Ice Thickness Measurements

Ice thickness was measured on a one metre grid using a graduated L-shaped rod. At each grid intersection, a 30 mm hole was drilled, the rod inserted and pulled up until the horizontal rod firmly contacted the lower ice surface. Ice thickness was then read and recorded on a grid chart. This operation was performed from a moveable carriage above the ice surface.

Several ice thickness contours were prepared during each test, and are referred to in this report as T_x, where x is the ice thickness measurement number for that test.

Additional qualitative observations were obtained from a video record of Tests 002 and 007.

3.7 Test Set-Up

The bubbler type and location for each test is illustrated in Figure 3.3.

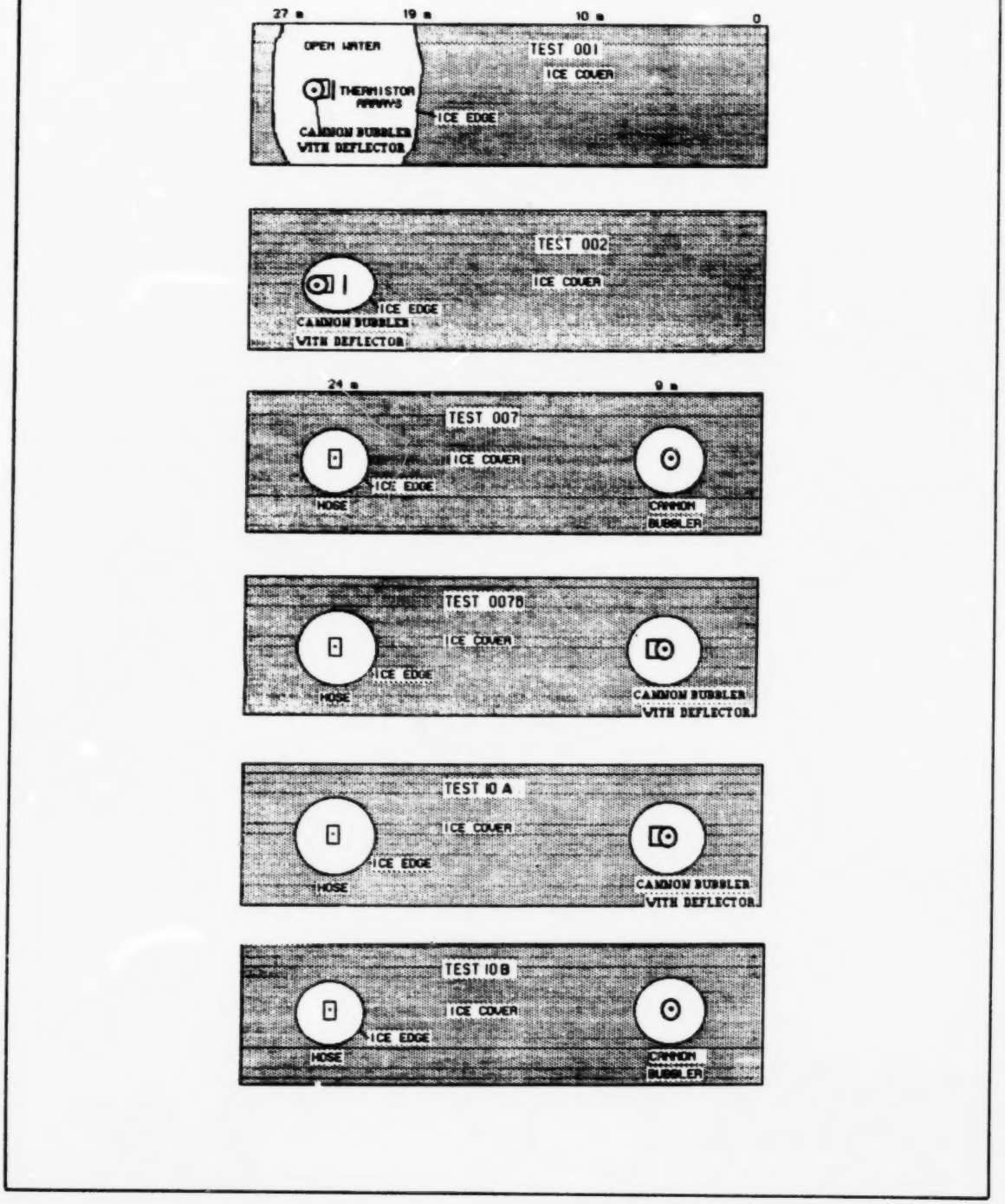


FIGURE 3.3 BUBBLER TEST SET-UP

4. RESULTS

4.1 Summary

This section presents observations made during the experiments. Each test result includes the following data:

(1) Plots of air temperature, water temperature, bubbler type and rate versus time. Times at which ice thicknesses were measured are shown.

(2) Profile plots of ice thickness against distance along test basin, each time ice thickness was measured.

(3) Plots of bubbler hole diameter versus time. Where two types of bubbler were used in one test, two curves are given.

Detailed profile plots of water temperature are given in Appendix A and contours of ice thickness are given in Appendix B.

Data from all tests are summarized in Table 4.1.

The results are analyzed in Section 5.

4.2 Test 001

Experimental conditions during Test 001 are summarized in Figure 4.1, which shows the mean air and water surface (15 cm depth) temperatures plotted against time. Also shown are the bubbler type, discharge rate and the times at which ice thickness was measured. (T_1 = hour 24.75, T_2= hour 27.0, T_3= hour 30.2 and T_4= hour 46.7). Water temperature profiles are given in Appendix A. During Test 001, the air bubbles were allowed to escape through an outlet at the top of the cannon prior to exiting the deflector.

Profiles of ice thickness down the centreline of the basin at the four time periods, T_1 through T_4, are shown in Figure 4.2. Detailed ice thickness measurements are included in Appendix B.

Test 001 was a freezing test that began with open water. Ice subsequently grew to 28 cm as the test progressed, the ice grew in thickness, with the rate of growth tending to increase with distance from the bubbler (Table 4.2). This suggests that the bubbler suppressed ice growth, although growth was not prevented entirely. Also, growth rate increased with time, corresponding with a decrease in water temperature.

A freezing pattern is exhibited in Figure 4.3, which shows the change in diameter of the bubbler hole.

Under the test conditions of water temperature 0.3°C and air temperature between - 20 and - 8°C, the bubbler slowed the rate of ice growth but did not melt already formed ice.

TABLE 4.1

SUMMARY OF OBSERVATIONS

DATE	TIME	TEST HOUR	TEST #	MEAN WATER TEMP. (°C)	BUBBLER RATE (SCFM)	(2) BUBBLER TYPE	(3) ICE COND. (E/G)	BUBBLER HOLE EXPANSION RATE (cm/hr/°C)	(1) MEAN AIR TEMP. (°C)	(4) ICE SHEET SUPPRESSION (Y or N)
NOV 17	15:30	23.5	001	1.10	T_2 60	D	G	- 36	- 15.5	Y
NOV 18	9:25	41.5		0.80	T_3 60	D	G	- 32	- 12.0	Y
	15.30	47.6		0.40	T_4 60	D	G	- 65	- 12.0	Y
NOV 24	12:50	27.0	002	0.6	T_2 75	D	E	+120	- 5.0	Y
	16:00	30.2		0.6	T_3 75	D	E	+ 83	- 5.0	Y
	08:20	46.7		0.6	T_4 75	D	E	+ 25	- 5.2	Y
NOV 29	13:15	28.5	007	0.36	T_2 70	H	G	- 75	- 4.3	N
DEC 1	09:30	69.8		0.20	T_4 70	H	E	+ 20	- 2.8	Y
	14:10	74.5		0.18	T_5 70	H	E	+ 17	- 2.3	Y
DEC 2	09.30	93.8		0.17	T_6 70	H	E	+ 23	- 2.7	N
NOV 30	09:30	47.8		0.21	T_3 70	C	G	- 05	- 3.2	N
DEC 1	09:30	69.8		0.20	T_4 70	C	E	+ 05	- 2.8	N
	14:10	74.5		0.18	T_5 70	D	E	+ 11	- 2.3	-
DEC. 2	09:30	93.8		0.17	T_6 70	D		0	- 2.7	
DEC 9	08:50	19.0	010	1.00	T_2 65	C	E	+ 18	- 5.5	Y
	13:50	24.0		0.40	T_3 65	C	G	- 37	- 5.0	Y
DEC 12	09:50	67.9		0.15	T_4 65	C	E	+ 20	- 5.1	N
DEC 9	08:50	19.0		1.00	T_2 65	H	E	+ 18	- 5.5	-
	13:50	24.0		0.40	T_3 65	H	G	- 25	- 5.0	N
DEC 12	09:50	67.9		0.15	T_4 65	H	G	- 13	- 5.1	N

(1) Temperatures are mean for period T_{n-1} to T_n

(2) C - cannon
D - deflector
H - hose

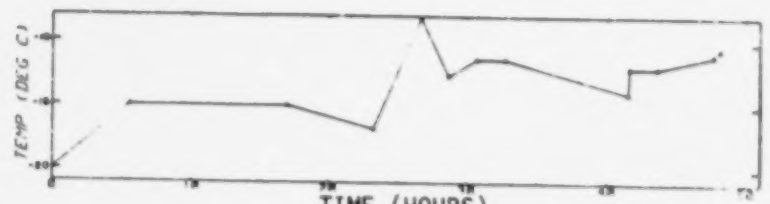
(3) E - erosion of ice edge
G - growth of ice edge

(4) Ice Sheet Suppression: N - no if bubbler hole walls vertical, or if slope away from bubbler is constant from T_{n-1} to T_n
Y - yes if ice sheet growth away from bubbler is suppressed.

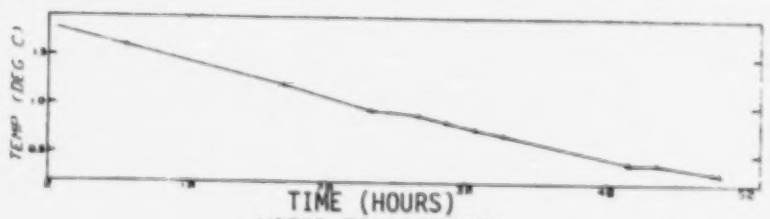
TABLE 4.2

ICE THICKNESS GROWTH RATE FOR TEST 001
(mm/hr)

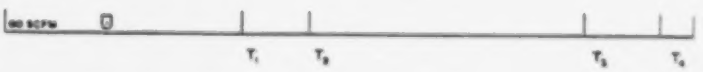
TIME (hours)	DISTANCE FROM BUBBLER (m)						
	5	7	8	10	12	14	16
0 T_0	OPEN WATER						
23.5 T_1	0	.9	.8	.6	1.5	1.9	2.0
41.5 T_2	.3	.8	.6	.9	1.0	1.0	1.2
48.0 T_3	1.4	1.0	1.2	3.0	1.4	2.4	1.8



AIR TEMPERATURE



WATER TEMPERATURE



BUBBLER TYPE
- CANNON
- DEFLECTOR
- HOSE

T_n INDICATES ICE THICKNESS MEASUREMENT

TIME 0 : NOV. 15, 1983 at 19:00

FIGURE 4.1 TEST 001 SCHEDULE

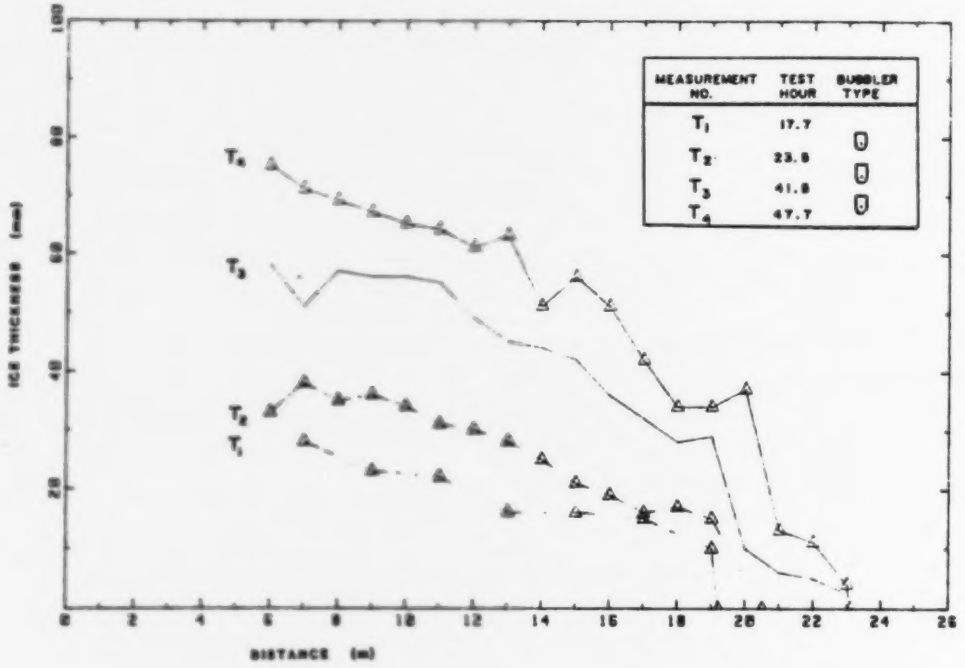


FIGURE 4.2 ICE THICKNESS PROFILES FOR TEST 001

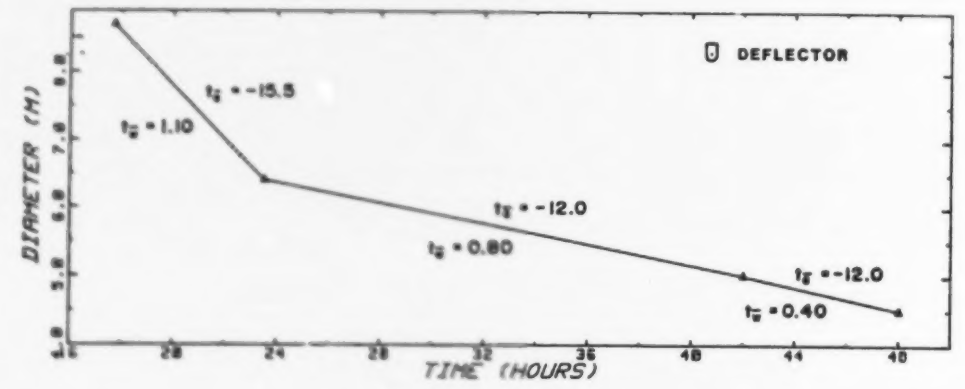


FIGURE 4.3 BUBBLER HOLE DIAMETER FOR TEST 001

4.3 Test 002

4.3.1 Ice Suppression

Figure 4.4 illustrates the schedule and temperature measurements for Test 002, while water temperature profiles are given in Appendix A. This test was performed under warmer air and water temperatures than Test 001, with a higher bubbler rate and with a deflector installed on the cannon bubbler.

The ice thickness history for Test 002 is summarized in Figure 4.5, and ice thickness maps are given in Appendix B. A separate profile is given for each of the four times ice thickness was measured.

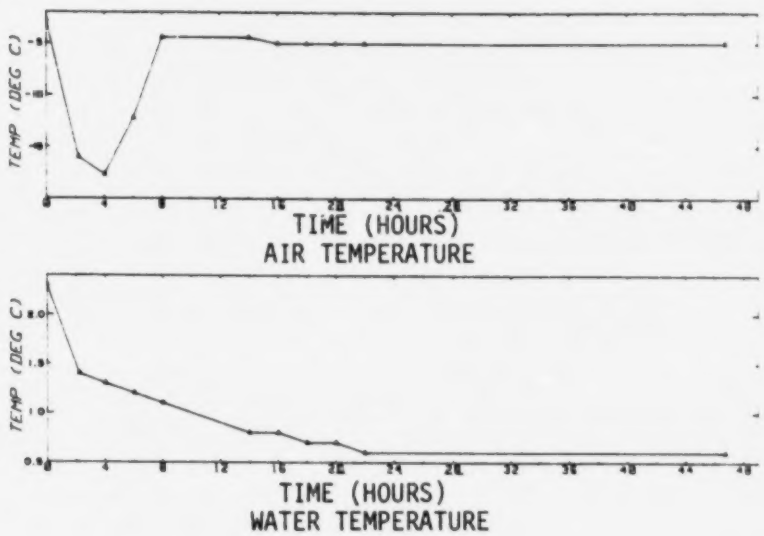
In all periods, ice thickness was constant approximately 8 m beyond the bubbler location. In the vicinity of the bubbler, ice thickness decreased with time, and bubbler hole diameter also increased with time. (Note that instruments were moved at approximately hour 26, and this might explain the brief decrease in bubbler hole diameter shown on Figure 4.6.

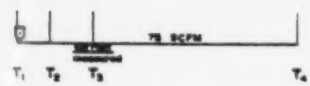
Figure 4.6 illustrates the change in bubbler hole diameter in more detail. For periods after T_2, the diameter increased continuously, with the highest rates coinciding with maximum water temperatures (greater than 1.8°C).

The deflector suppressed ice growth in the vicinity of the bubbler, and caused an increase in the area of open water under the test conditions of water temperature 0.6° and air temperature - 5°C.

4.3.2 Current Velocity

Current velocities in front of the deflector are shown in Figures 4.7 and 4.8.



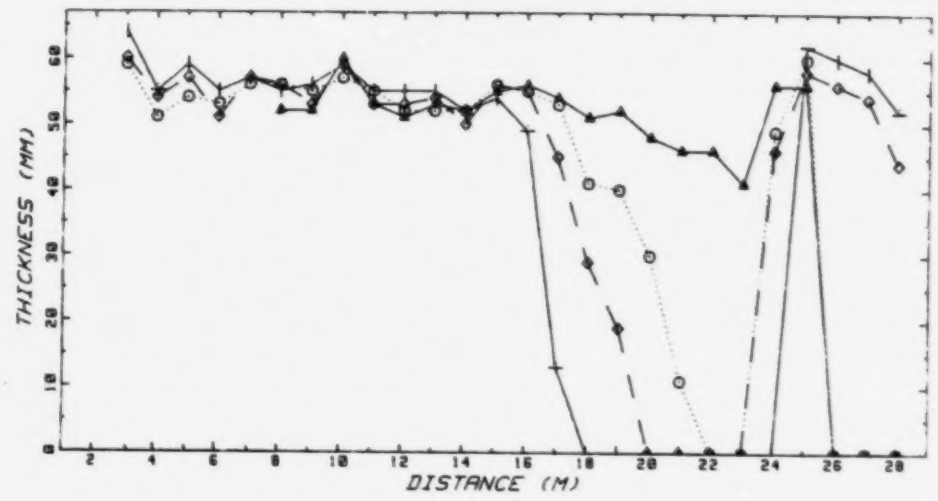


BUBBLER TYPE
- CANNON
- DEFLECTOR
- HOSE

T_n INDICATES ICE THICKNESS MEASUREMENT

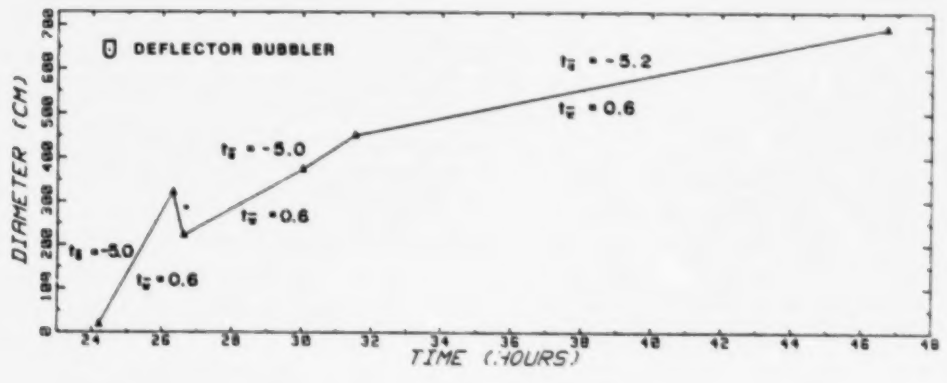
TIME 0 : NOV. 23, 1983 at 09:50

FIGURE 4.4 TEST 002 SCHEDULE



SYMBOL	MEASUREMENT NO.	TEST HOUR	BUBBLER TYPE
—△—	T_1	24.7	D
—○—	T_2	27.0	D
—◇—	T_3	30.2	D
—+—	T_4	46.7	D

FIGURE 4.5 ICE THICKNESS PROFILES FOR TEST 002



• INSTRUMENT MOVED APPROX. HOUR 26

FIGURE 4.6 BUBBLER HOLE DIAMETER FOR TEST 002

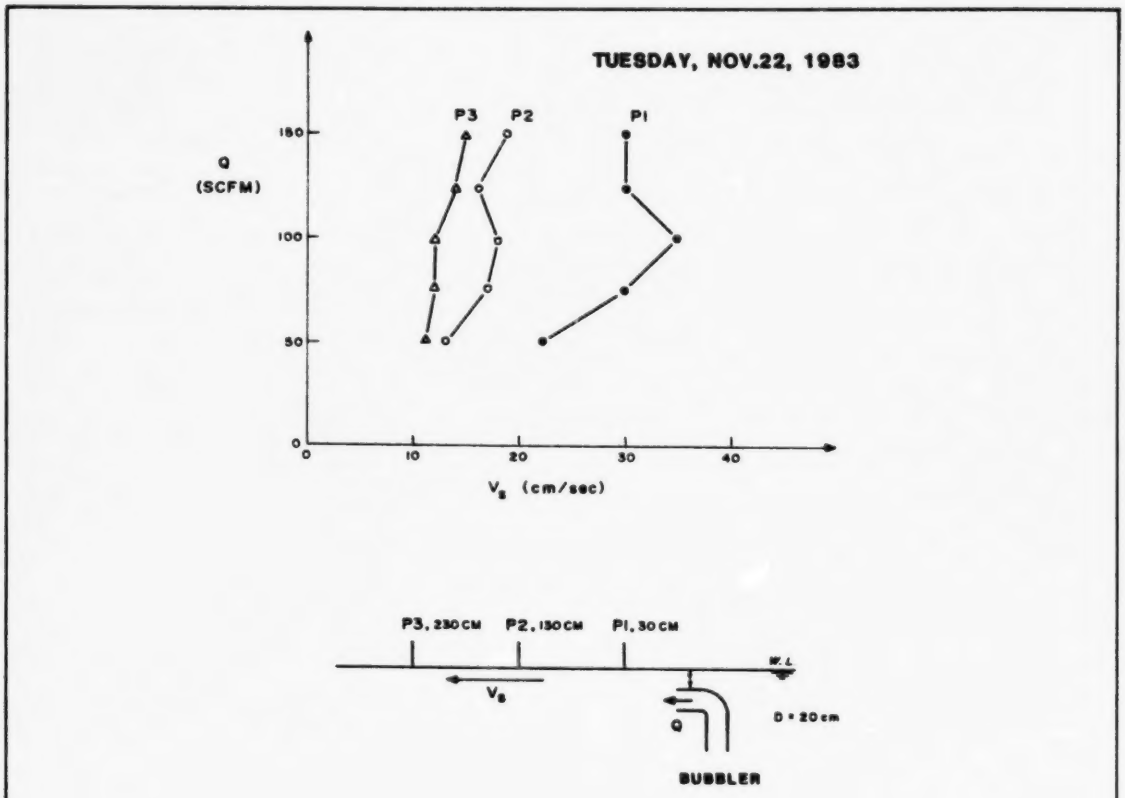


FIGURE 4.7 SURFACE VELOCITY VERSUS AIR FLOW RATE

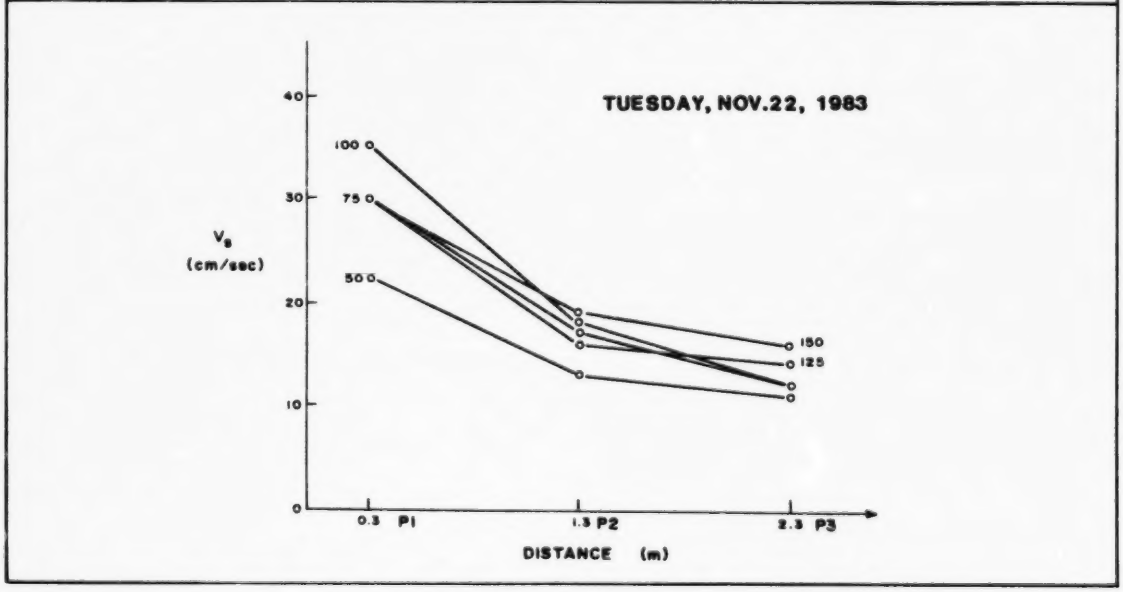


FIGURE 4.8 SURFACE VELOCITY VERSUS DISTANCE FROM BUBBLER

4.4 Test 007

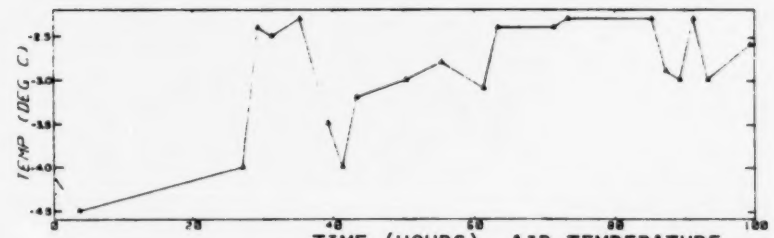
Test conditions for 007 are shown in Figure 4.9, and ice thickness profiles in Figure 4.10. Water temperature profiles are given in Appendix A and ice thickness measurements in Appendix B. Three bubbler types were used.

The cannon bubbler was used from T_2 to T_4, and located at the 9 m mark. Figures 4.10 and 4.11 show that the bubbler eroded the edge of the ice sheet, expanding the bubbler hole, but did not erode or suppress ice growth at the bottom of the ice sheet.

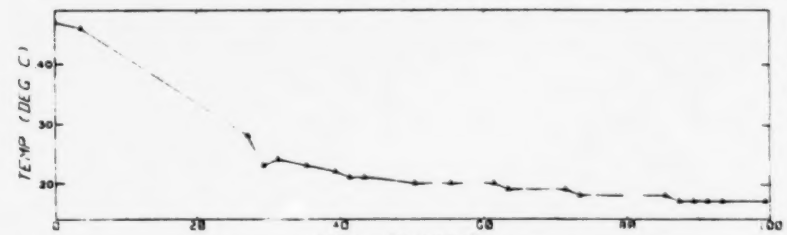
From T_4 to T_6, a deflector was installed on the cannon bubbler. Comparison of the profiles during this period indicate that the ice edge was not eroded, but ice growth at the bottom of the ice sheet was suppressed near the bubbler. The pattern of relative ice edge growth and melting is shown clearly in Figure 4.11.

A bubbler hose was installed at the 24 m mark, and operated as shown in Figure 4.9. During time period T_1 to T_2 the bubbler hole froze entirely to a thickness of 12 mm. The bubbler was operated again after T_3. Ice thickness shows complex variations, with a large increase in thickness to T_4, and more moderate decrease to T_5 and T_6. After T_2 the bubbler hole diameter increased continuously.

The hose bubbler maintained a slightly larger area of open water than did the cannon bubbler.



TIME (HOURS) AIR TEMPERATURE



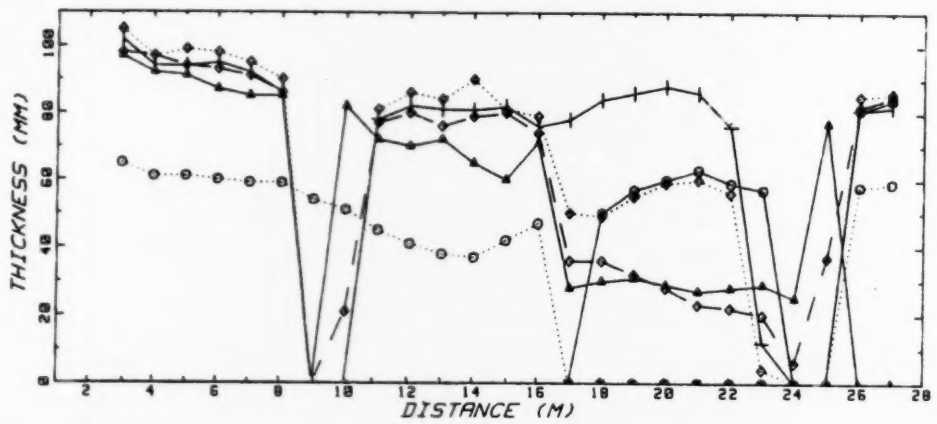
TIME (HOURS)
WATER TEMPERATURE

BUBBLER TYPE
- CANNON
- DEFLECTOR
- HOSE

T_n INDICATES ICE THICKNESS MEASUREMENT

TIME 0 : NOV. 28, 1983 at 09:40

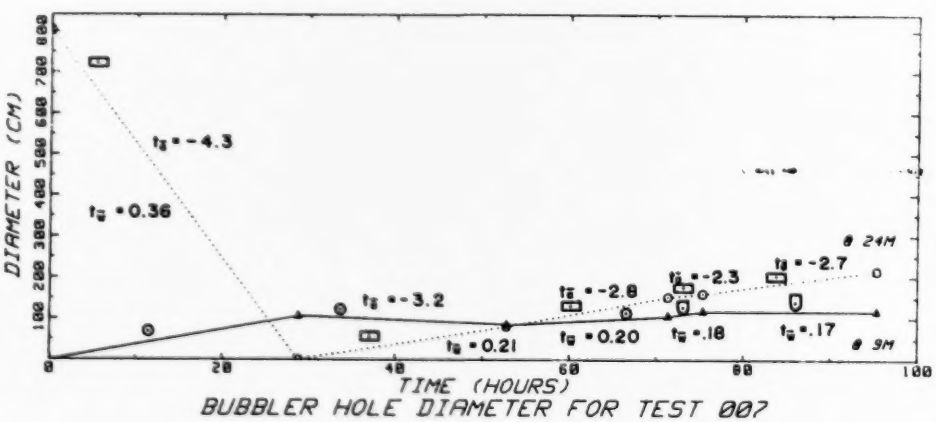
FIGURE 4.9 TEST 007 SCHEDULE



SYMBOL	MEASUREMENT NO.	TEST HOUR	BUBBLER TYPE at 9m	BUBBLER TYPE at 24m
	T_1	00	—	□
	T_2	28.5	⊡	—
	T_3	47.8	⊙	⊡
	T_4	69.8	⊙	⊡
	T_5	74.5	⊙	⊡
	T_6	93.8	⊙	⊡

⊙ INCOMPLETE MEASUREMENT

FIGURE 4.10 ICE THICKNESS PROFILES FOR TEST 007



BUBBLER HOLE DIAMETER FOR TEST 007

FIGURE 4.11 BUBBLER HOLE DIAMETER FOR TEST 007

4.5 Test 010

Test conditions for 010 are shown in Figure 4.12, while ice thickness profiles are shown in 4.13, water temperature profiles in Appendix A, and ice thickness measurements in Appendix B. A hose bubbler was used at the 24 m mark, and a cannon bubbler at the 9 m mark.

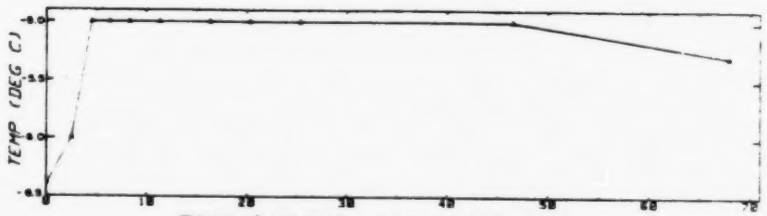
At the cannon bubbler site, almost no ice growth or melting occurred between T_2 and T_3. From T_3 to T_4, ice thickness grew, with an increasing rate with distance from the bubbler. From T_1 to T_2, a large amount of ice melted.

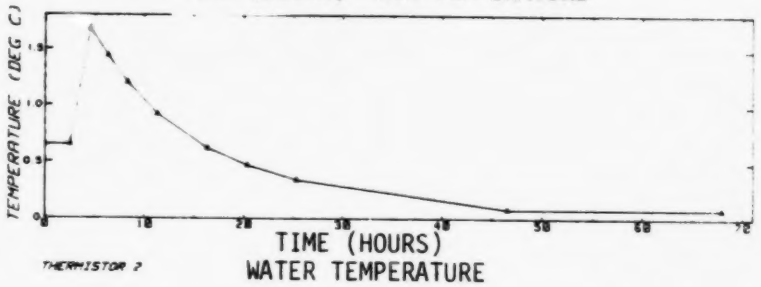
These patterns are paralleled by the change in bubbler hole diameter measurements given in Figure 4.14. The period of ice thickness growth and freezing over corresponds with relatively high air temperature and moderate water temperature (0.3 to 0.4°C), and cannot be explained with the data presented.

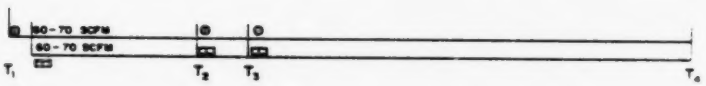
At the hose bubbler site, melting occurred at the bottom of the ice sheet from time T_2 to T_3, at a rate decreasing with distance from the ice sheet. From T_3 to T_4 the ice sheet grew in thickness on one side, at a rate increasing with distance from the bubbler. On the other side, the pattern of ice melting and growth was irregular. No data are available for the period T_1 to T_2.

The pattern of variation in bubbler hole diameter parallels that of ice growth, as it did for the cannon bubbler with deflector installed.

The cannon and hose bubblers exhibited qualitatively similar ice suppression capabilities. The hose bubbler maintained a slightly larger open water area than did the cannon bubbler.





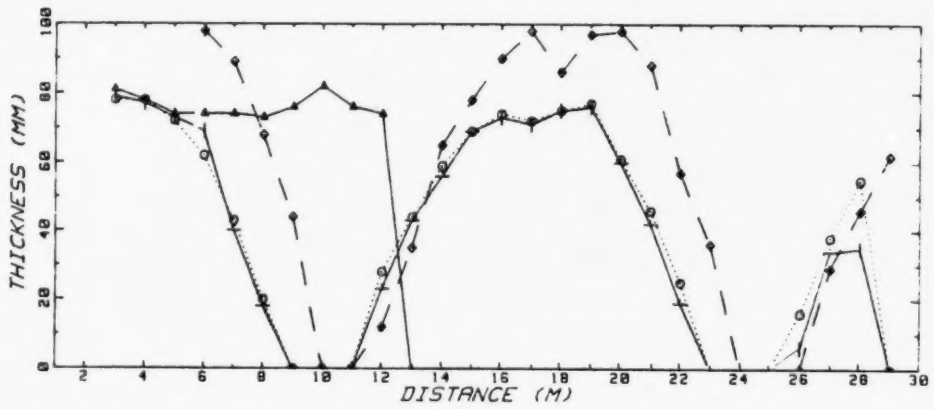


BUBBLER TYPE
- ⊖ CANNON
- ⊡ DEFLECTOR
- ▭ HOSE

T_n INDICATES ICE THICKNESS MEASUREMENT

TIME 0 : DEC. 8, 1983 at 1400

FIGURE 4.12 TEST 010 SCHEDULE



SYMBOL	MEASUREMENT NO.	TEST HOUR	BUBBLER TYPE at 10m	BUBBLER TYPE at 24m
—△—	T_1	00	⊙	⊡
···○···	T_2	19.0	⊙	⊡
—+—	T_3	24.0	⊙	⊡
—◇—	T_4	67.9		

⊡ INCOMPLETE MEASUREMENT

FIGURE 4.13 ICE THICKNESS PROFILES FOR TEST 010

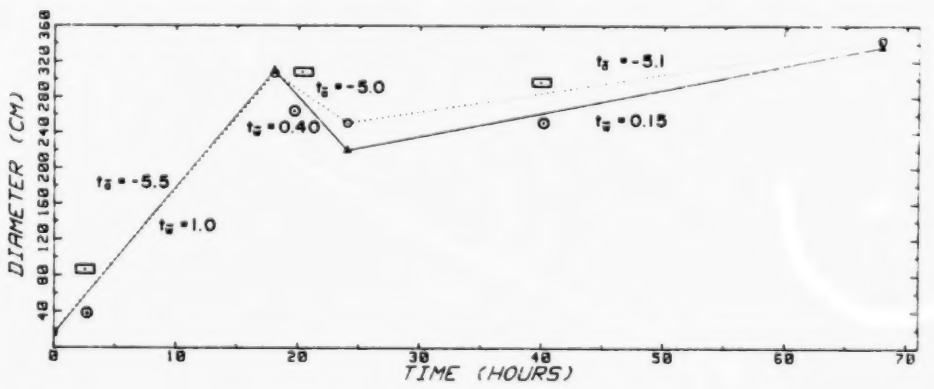


FIGURE 4.14 BUBBLER HOLE DIAMETER FOR TEST 010

5. ANALYSIS

5.1 Flow Development

5.1.1 Calculation and Measurement

Horizontal flow development is the result of the bubble rising velocity, efficiency of vertical entrainment, horizontal entrainment and dispersion of the horizontal flow.

Wegener and Parlange [8] modelled the bubble rising velocity as:

$$U_B = \sqrt{\frac{gD}{2}} \qquad (5.1)$$

where U_B = rising velocity
g = gravitational constant
D = bubble diameter

The efficiency of entrainment by the rising bubble is reduced by head losses at the bubbler pipe inlet, the elbow, the deflector outlet and in the bubbler pipe itself. Empirical data from tests conducted by the manufacturer indicates that an efficiency factor of 0.75 to 0.80 describes the sum of these losses [9].

Velocity of the bubbler outlet is described as:

$$U_o = \alpha \left(\frac{A_o}{A_p}\right) U_B \qquad (5.2)$$

and discharge as:

$$Q_o = A_o U_o \qquad (5.3)$$

where U_o = mean horizontal velocity from deflector outlet
α = efficiency factor (0.79 for the bubbler used)
A_o = area of deflector outlet
A_p = area of bubbler pipe
U_B = bubble rising velocity.
Q_o = discharge at the bubbler outlet

For the bubbler, A_p = 81.1 cm^2
A_o = 17.7 x 6.35 cm
U_B = 0.71 m/sec
α = .79

and therefore, U_o = .78 m/sec and bubbler discharge,
Q_o = 8.8 x 10^{-3}m^3/sec.

After exiting the deflector, the horizontal flow is dispersed to an increasing area, and therefore the mean velocity decreases exponentially. The change in velocity with distance from the bubbler is shown in Figure 5.1, assuming a constant angle of divergence of flow of 15°.

Figure 5.1 clearly indicates the rapid decrease in vertical velocity as the plume area increases.

Actual mean velocities from the laboratory tests are also shown in Figure 5.1. These were obtained during Test 002 at an air discharge of 75 SCFM in open water, and show a much lower reduction with distance than expected from the calculations. It is hypothesized that this is due to a lower divergence rate than that used in the model (eg. 15°).

Flow development during the laboratory tests can also be assessed empirically using the ice thickness measurements. The results shown in Table 5.1 suggest that the cannon bubbler suppressed the ice cover at a greater distance than did the hose bubbler (Test 010) and that the cannon with deflector suppressed the ice cover at a greater distance than did either the cannon without deflector or the hose bubbler (Test 007). The radius of suppression was 3 to 5 metres for the hose bubbler, 3 to 7 metres for the cannon bubbler and 5 to 9 metres for the cannon bubbler with deflector.

An additional observation was made during the laboratory tests concerning flow development; velocity increased with air discharge from 50 to 100 SCFM, and then decreased at 125 SCFM. This was due to exceeding the optimum air bubble volume to generate the maximum discharge. A very large volume of air will reduce the discharge due to the space occupied by the air rather than water. A similar decrease in efficiency at high air discharge rates was observed in tests reported by Atara Corporation [9].

5.1.2 Scaling

Based on Froude scaling laws, the scaling of the rising bubble speed is given by:

$$U_B = (gr)^{\frac{1}{2}} \tag{5.4}$$

where U_B = rising bubble speed
r = bubble radius
g = gravitational constant
λ = scaling factor

$$\lambda U_B = g^{\frac{1}{2}} \lambda r^{\frac{1}{2}} = \lambda r^{\frac{1}{2}} = \sqrt{\lambda} L^{-} \tag{5.5}$$

Water discharge is scaled as:

$$Q = \alpha \frac{\pi D^2}{4} U_B \tag{5.6}$$

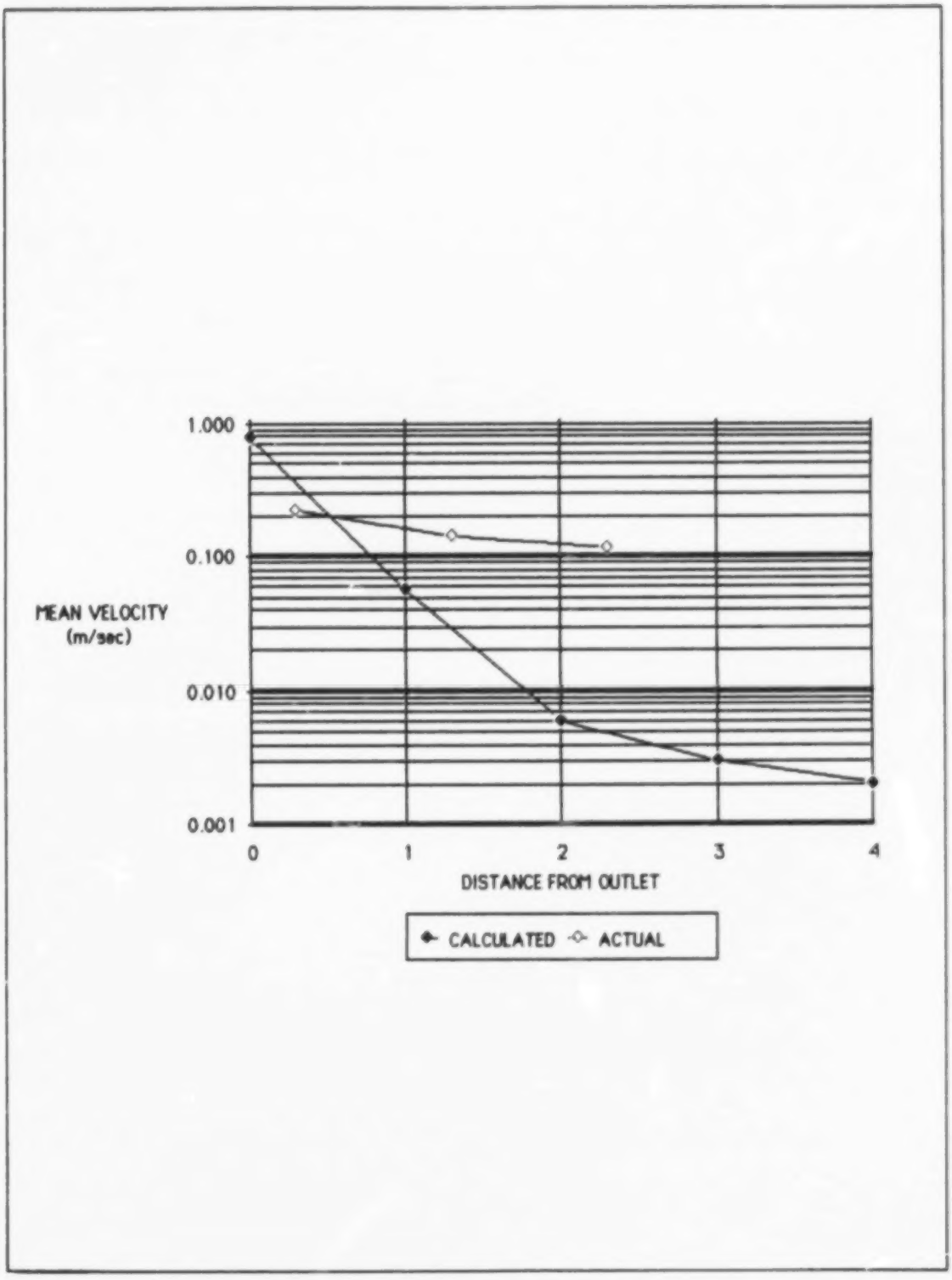


FIGURE 5.1 HORIZONTAL VELOCITY

TABLE 5.1

RADIUS OF MELTING BENEATH ICE COVER

TEST	TIME PERIOD (ENDING)	BUBBLER TYPE			MEAN TEMP.(°C)		AIR DISCHARGE (SCFM)
		CANNON	CANNON WITH DEFLECTOR	HOSE	AIR	WATER	
001	No data; initial ice thickness was not uniform						60
002	T_2		7m		-5.0	0.60	75
	T_3		8m		-5.0	0.60	75
	T_4		9m		-5.2	0.60	75
007	T_4	3m		3m	-2.8	0.20	70
	T_5			3m	-2.3	0.18	70
	T_6		5m	3m	-2.7	0.17	70
010	T_2	6m			-5.5	1.00	65
	T_3	6m		5m	-5.0	0.40	65
	T_4	7m		4m	-5.1	0.15	65

where Q = discharge per unit area
α = efficiency factor (0.79 for the bubbler used in this test)
D = diameter of the pipe outlet

$$\lambda_Q = \alpha \cdot \frac{\pi}{4} \lambda^2 L \sqrt{\lambda L}$$

$$\lambda_Q = \lambda L^{5/2} \qquad (5.7)$$

5.2 Heat Transfer

5.2.1 Heat Transfer Rate

The heat transfer rate from a turbulent flow moving horizontally under an ice cover is given by the following relationship [Rohnsenou and Choi, 1961]:

$$N_u = C\, R_e^{0.8}\, Pr^{0.4} \qquad (5.8)$$

where N_u = Nusselt Number

C = Coefficient ($\cong$.023)

R_e = Reynolds Number

Pr = Prandlt Number

For near freezing point, Ashton [9], presented the following simplified relationships:

$$h = 1622 \frac{U^{0.8}}{D^{0.2}} \quad W/m^2/°C \qquad (5.9)$$

where h = rate of heat transfer
U = mean horizontal velocity
D = Depth or diameter of the flow

Thus, the rate of heat transfer to the water/ice surface can be calculated at any radius from the bubbler. Figure 5.2 shows the heat transfer rate at the bubbler outlet and at 1 metre radius intervals. Area (A) and depth (D) are calculated assuming a 15° rate of divergence of the horizontal plume in both X and Y directions and velocity is calculated as Q/A. The rate of heat transfer per unit area decreases exponentially with distance, while the surface area exposed to the heat transfer increases. The average rate of heat transfer over a six metre radius is 497 $W/m^2/°C$. The rate of heat transfer calculated from observed horizontal velocities is also shown on Figure 5.2.

The spatial distribution of the heat transfer rate has important consequences in that the highest rates are concentrated near the bubbler. In this situation, large amounts of heat will be lost through open water areas. For example, the mean rate of heat transfer for the conditions considered above is 1710 $W/m^2/°C$ over the first metre radius from the bubbler. For a typical ice thickness of 75 mm, this small area

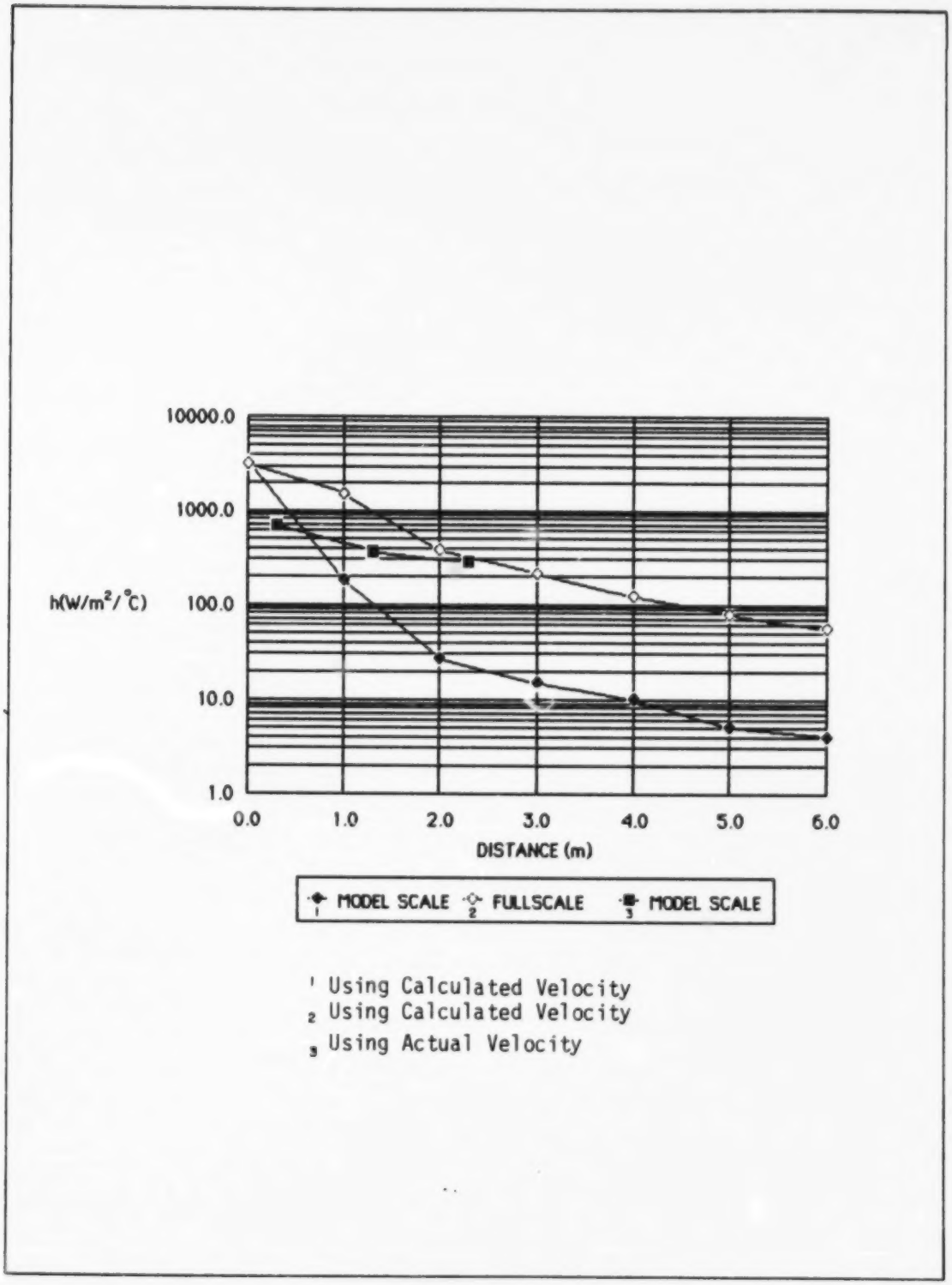


FIGURE 5.2 CALCULATED RATE OF HEAT TRANSFER

would be ice free after 0.4 hours and heat would be lost from the open water surface thereafter.

5.2.2 Ice Melting

The theoretical rate of heat transfer can be compared with observed ice melting in the laboratory tests. Over a six metre radius, the mean calculated heat transfer rate is 497 $W/m^2/°C$, capable of melting ice at a rate of 5 mm/hr/°C over the 10.7 m^2 area. This is equivalent to a melting rate of 1.9 mm/hr/°C for a 6 m length of the test basin (30 m^2). The following assumptions are made:

- no heat loss from open water or from the ice surface to the air
- bottom surface of ice cover is at 0°C.
- angle of divergence is 15°
- test basin is 30 m^2, surface area of bubbler plume is 10.7 m^2

Actual ice melting rates and bubbler (installation) hole expansion rates are compared with calculated melting rates in Table 5.2. This table shows that the observed rate of ice melting (growth) is not correlated with other experimental parameters, nor with calculated rates. This can be explained by the method of measurement. The 'observed rate' is the mean over a 6 metre length of the test basin. This length was chosen because it was the maximum radius of ice suppression for most of the tests. Ice melting was not uniform across the basin however, and the data in Table 5.2 represents the mean for areas of both ice growth and ice suppression. Thus, where a positive change of ice thickness is reported in Table 5.2, ice growth in the 6 metre section of the test basin exceeded ice melting in front of the bubbler. For this reason, 'observed ice growth/suppression' and 'observed change in bubbler hole radius' are more representative of bubbler performance.

The cannon bubbler suppressed ice growth locally in all cases, and enlarged the bubbler hole when air flow exceeded 60 SCFM. The maximum rate of enlargement coincided with maximum air flow rate. This is in agreement with the observations on velocity and flow rate reported earlier.

5.2.3 Comparison of Bubblers

Data in Table 4.1 allows comparison of ice suppression among the three types of bubblers used in the tests. In terms of suppressing ice growth ahead of the bubbler, the deflector was successful in all six tests versus two of the six tests for the hose bubbler and two of five tests for the cannon without deflector.

In terms of erosion of the bubbler hole edge, the deflector was successful in four of six tests, the hose bubbler in four of six tests, and the cannon without deflector in three of five tests.

TABLE 5.2

HEAT TRANSFER AND MELTING RATE

FOR CANNON BUBBLER WITH DEFLECTOR

TEST	T (°C) AIR	T (°C) WATER	AIR FLOW (SCFM)	OBSERVED LOCAL ICE GROWTH/ SUPPRESSION	CHANGE IN ICE THICKNESS (mm/hr)		OBSERVED CHANGE IN BUBBLER HOLE RADIUS (cm/hr)
					CAL.	OBS.	
001 T_2	-15.5	1.1	60	S	-1.7	+0.3	-36
T_3	-12.10	0.8	60	S	-2.3	-0.1	-32
T_4	-12.0	0.4	60	S	-4.7	+4.2	-65
002 T_2	- 5.0	0.6	75	S	-3.2	+5.0	+120
T_3	- 5.0	0.6	75	S	-3.2	+2.2	+ 83
T_4	- 5.2	0.6	75	S	-	-	+ 23
007 T_5	- 2.3	0.2	70	S	-	-	+ 11
T_6	- 2.7	0.2	70	S	-	47.0	0.0

5.2.4 Scaling of Heat Transfer

Assuming a factor of four to full scale, the diameter would increase by four times and the bubble rising velocity by two ($\lambda U_B = \sqrt{\lambda L} = \sqrt{4}$) Bubble velocity, area and ice suppression at full scale are shown in Table 5.3.

The average heat transfer within the 29.6 m² full scale surface area of the six metre radius is 893.3 W/m²/°C, capable of melting 1 cm/hr/°C of ice using the assumptions given in 5.2.1 above, over an area of 29.6 m².

TABLE 5.3

FULL SCALE CALCULATIONS

U_o = 1.56 m/sec A_o = .708 x .254 m² Q_o = .280 m³/sec

DISTANCE (m)	A(m²)	D(m)	U(m/sec)	h(W/m²/°C)
0	.180	.254	1.56	3046
1	.327	.850	0.86	1482
2	1.649	1.350	0.17	370
3	3.119	1.850	0.09	209
4	5.089	2.350	0.05	119
5	8.119	2.950	0.03	79
6	11.189	3.450	0.02	55
	29.6			5360

h = 893.3 W/m²/°C

6. CONCLUSIONS

6.1 Flow Development

The cannon bubbler with deflector resulted in ice melting to a greater radius than did the other bubblers tested. In a test with air discharge of 75 SCFM, air temperature of -5.2°C and water temperature of 0.60°C the radius reached 9 metres. Comparison of actual and calculated horizontal flows showed that the bubbler performed better than predicted by the model in terms of flow development. This could be a result of the rate of flow divergence assumed by the model. The highest velocity flows were developed by the cannon bubbler at an air flow rate below the maximum tested. This observation is in agreement with previous tests which showed decreasing efficiency at high air discharge rates [9].

6.2 Heat Transfer

The volume of ice melted by the air cannon bubbler was substantially lower than predicted by Ashton's model for forced convection [7]. An average heat transfer coefficient of 497 $W/m^2°C$ was computed according to Ashton giving an average melting capacity of 1.9 mm/hr/°C over the test basin area of 30 m^2. The heat transfer model used did not agree well with observed ice melting rates.

At full scale (factor of four) the bubbler would be capable of melting 1 cm/hr/°C, following Ashton's model.

6.3 Cannon vs. Conventional Bubbler

The air cannon bubbler with deflector installed was more efficient than the standard air cannon bubbler or the conventional bubbler, at generating horizontal flow. It also suppressed ice growth in a higher percentage of cases than did the other bubblers.

7. RECOMMENDATIONS

1. The air cannon bubbler with deflector should be used to suppress ice at Thunder Bay and other ice-prone harbours because it is more successful than the air cannon without deflector or than the conventional bubbler, in generating horizontal flow and in suppressing ice growth.

2. Additional tests should be undertaken to assess bubbler efficiency and horizontal flow development under a variety of air flow rates. These tests should also measure the horizontal flow ahead of the bubbler, to allow estimation of the rate of divergence of the horizontal plume.

8. REFERENCES

[1] Hill, J.E., "Air Bubbler Ice Control Experiment in Thunder Bay", Lakehead Harbour Commission, report for Transport Canada, May 1980.

[2] Kamo, H.R., and D.A. Nelson "Air Bubbler Ice Control Experiments in Thunder Bay, Ontario", report prepared for the Lakehead Harbour Commission by V.B. Cook Company Limited, 1982.

[3] Kamo, H.R., and D.A. Nelson "1982-83 Air Bubbler Ice Control Experiment in Thunder Bay, Ontario", report prepared for Lakehead Harbour Commission and Transport Canada by V.B. Cook Company Limited, 1983.

[4] Abdelnour, R., "Field Temperature Measurement in Thunder Bay Harbour (Winter 1983), Transportation Development Centre Report TP 4517, June 1983.

[5] Abdelnour, R., and M. Sayed, "Technological Alternatives to the Use of the CCGS Icebreakers at Thunder Bay Harbour", report prepared for Marine Research and Development - Energy, Transport Canada, by Arctec Canada Limited, 1982.

[6] Kamo, H.R. and D.A. Nelson, "Evaluation of the Atara Piston Bubbler Cannon Mixer for Ice Suppression Thunder Bay, Ontario, Report to TDC, Transport Canada, 1982.

[7] Ashton,G. D., "Theory of Thermal Control and Prevention of Ice in River and Lakes, Advances in Hydroscience (13)", CRREL, 1982.

[8] Wegener and Parlange, "Spherical Cap Bubbler", Annals Rev. Fluid Dynamics 5, p.99-100, 1973.

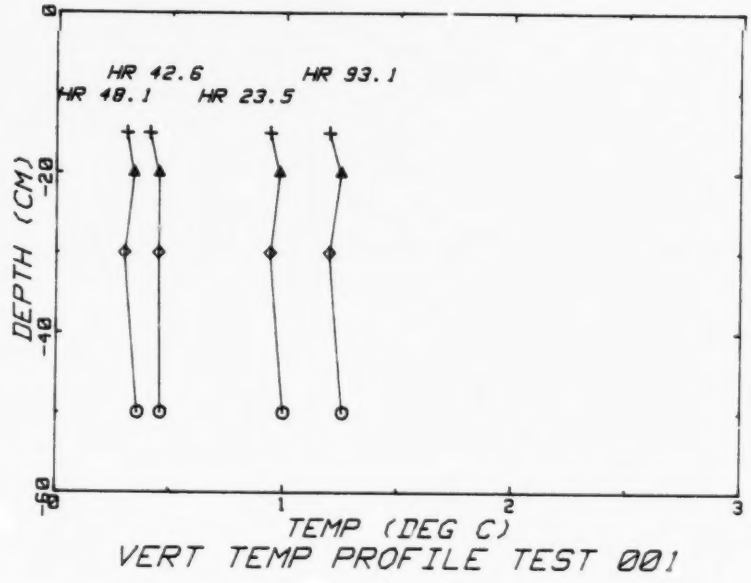
[9] Atara Corporation. Personal communication on technical paper to be presented by B. Grandjean.

APPENDIX A

WATER TEMPERATURE PROFILES

FIGURE A.1

WATER TEMPERATURES FOR TEST 001



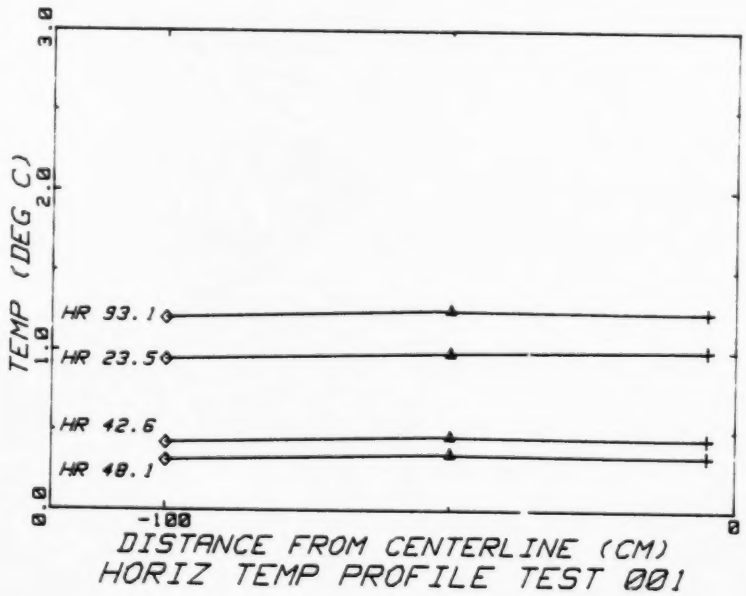
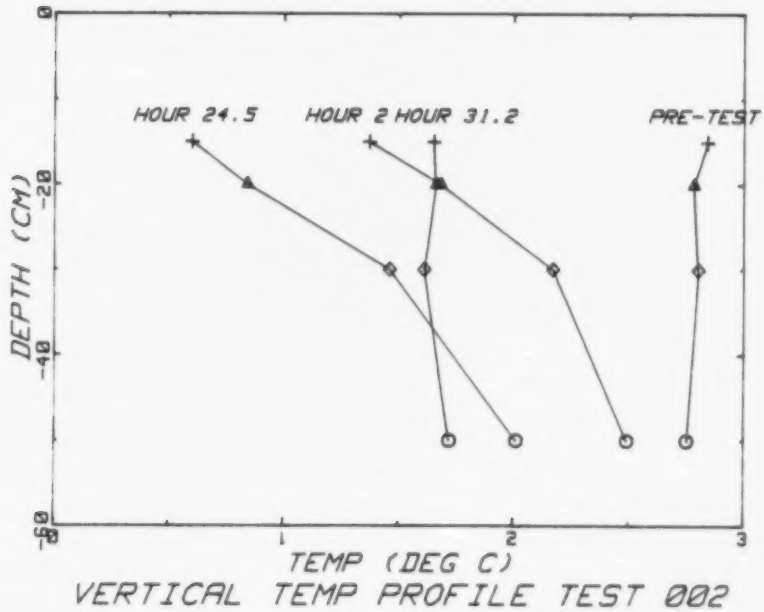
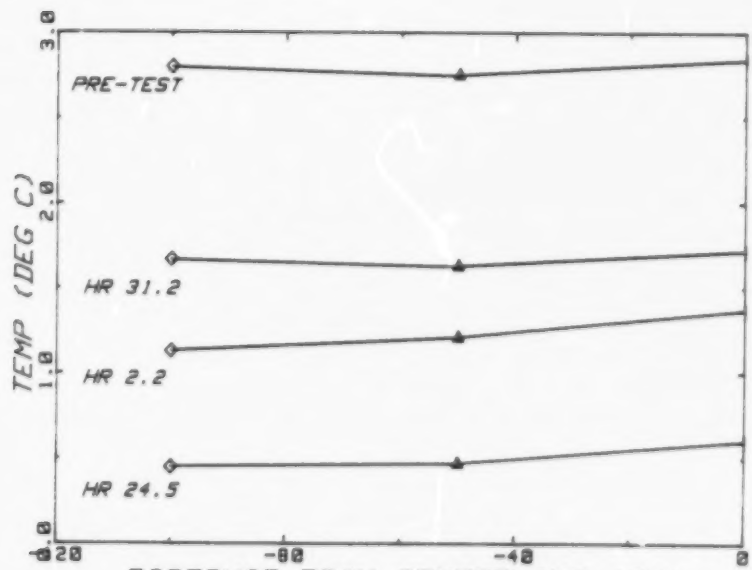


FIGURE A.2

WATER TEMPERATURES FOR TEST 002



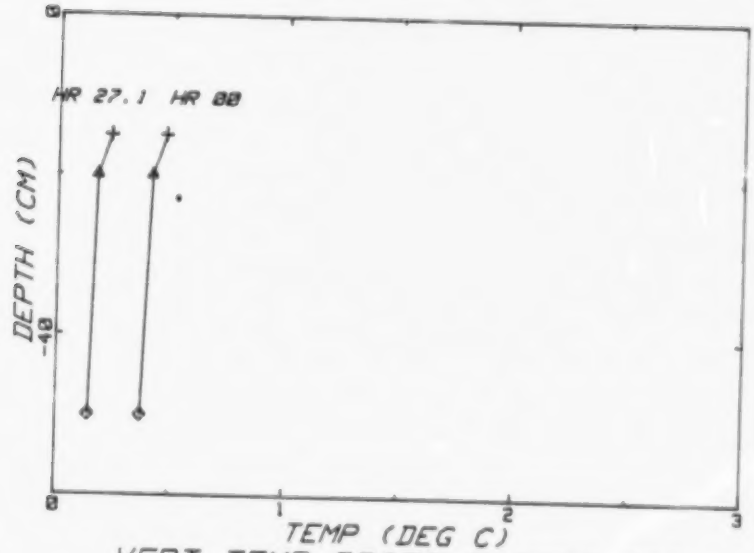
VERTICAL TEMP PROFILE TEST 002



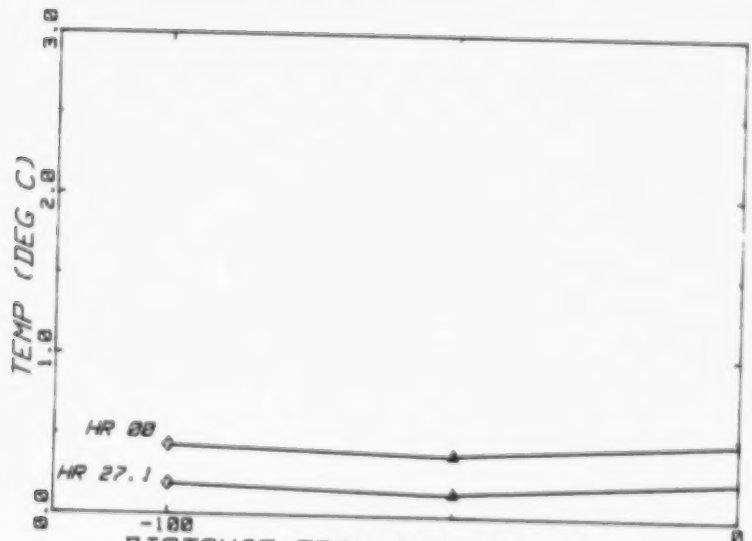
HORIZ TEMP PROFILE TEST 002

FIGURE A.3

WATER TEMPERATURES FOR TEST 007



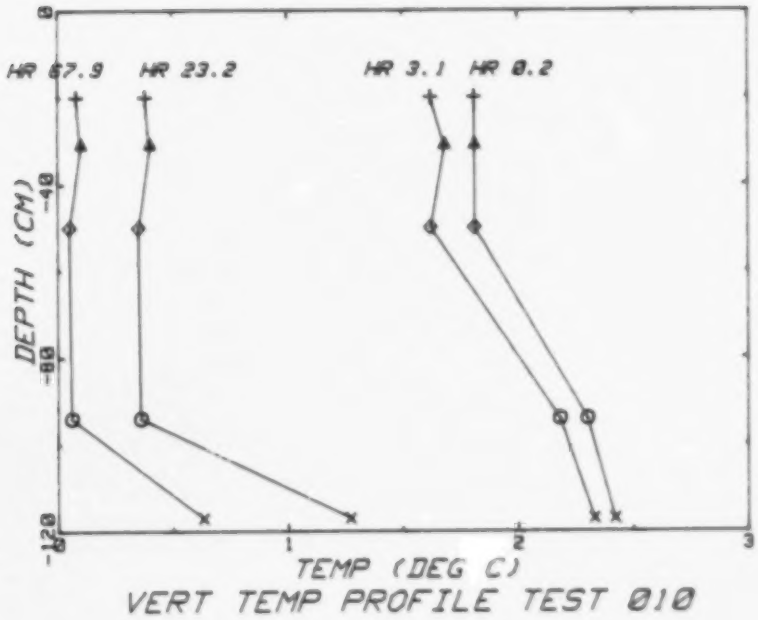
VERT TEMP PROFILE TEST 007



HORIZ TEMP PROFILE TEST 007

FIGURE A.4

WATER TEMPERATURES FOR TEST 010



HORIZONTAL PROFILE NOT AVAILABLE

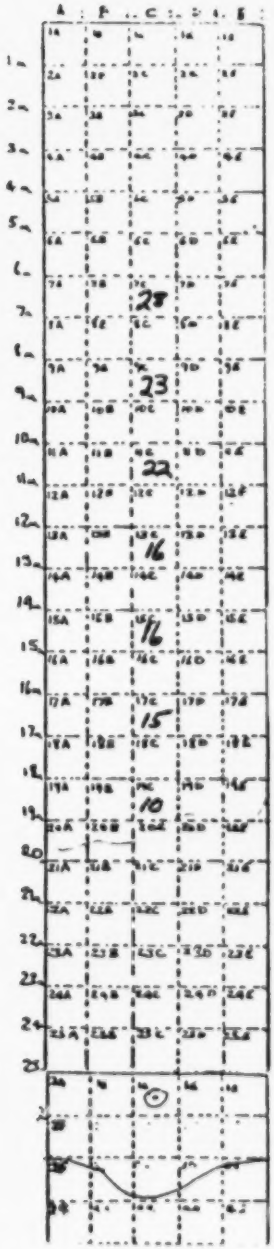
APPENDIX B

ICE THICKNESS CONTOURS

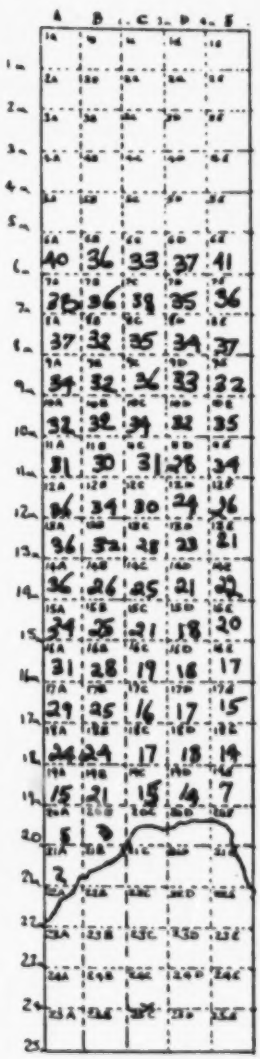
ICE THICKNESS

TEST 001

T_1 Hour 17.7

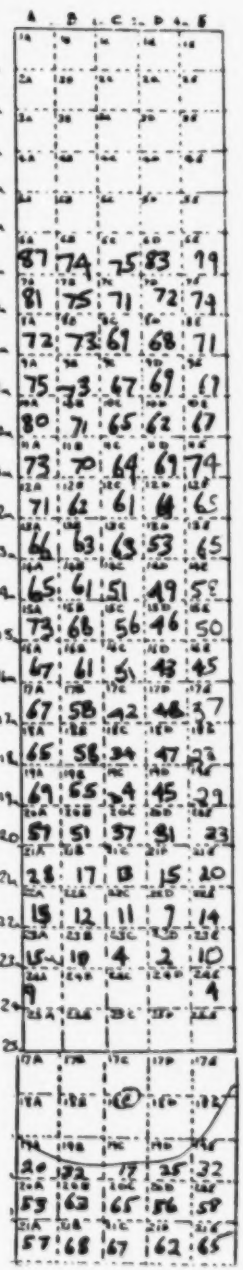


T_2 Hour 23.5



T_3 Hour 41.5

T_4 Hour 47.6

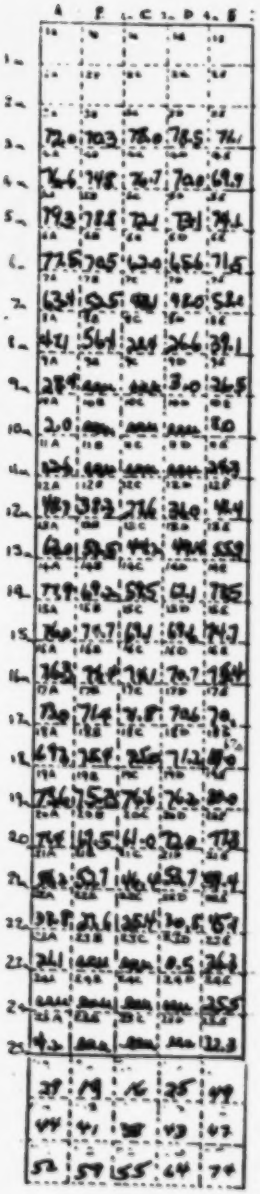


Ice thickness in mm
One metre grid

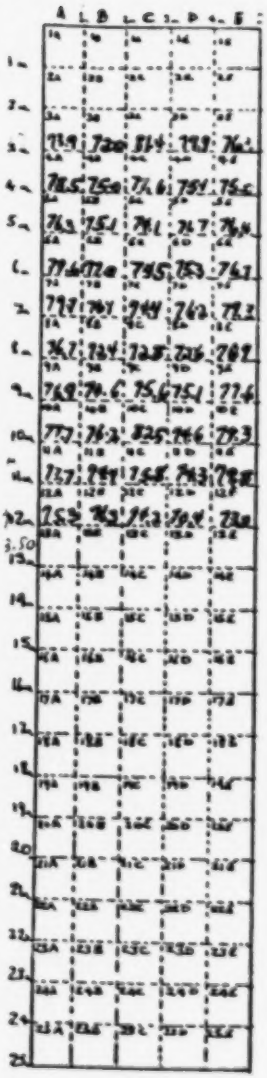
ICE THICKNESS

TEST 002

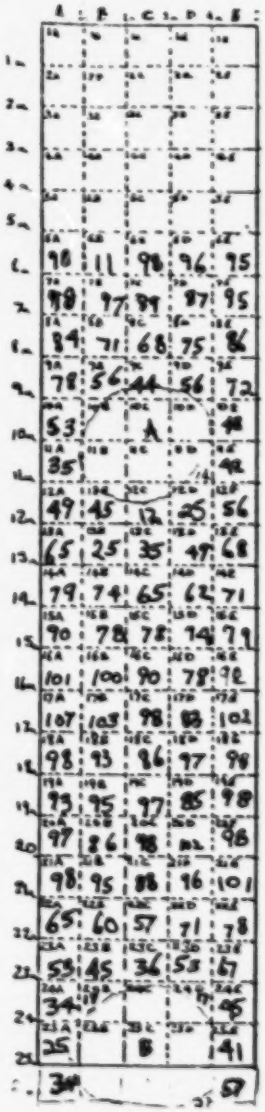
T_1 Hour 24.7



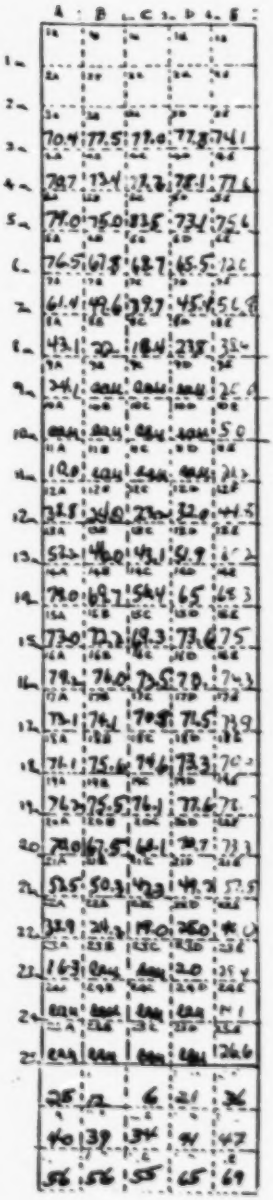
T_2 Hour 27.0



T_3 Hour 30.2



T_4 Hour 46.7

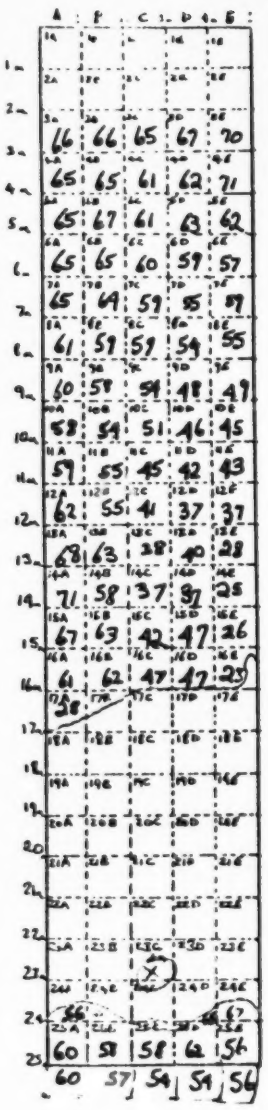


ice thickness in mm
1 meter grid

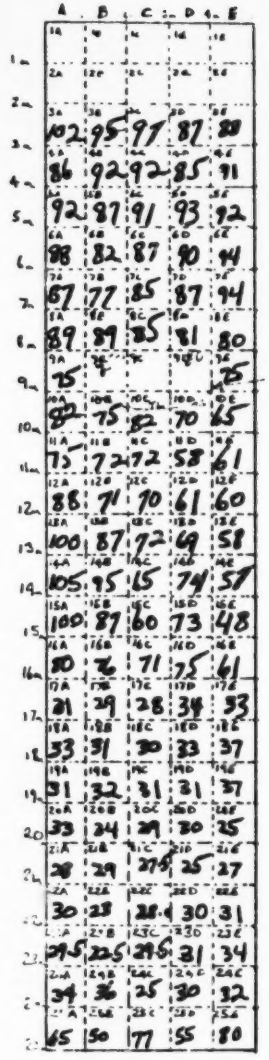
ICE THICKNESS

TEST 007

T_1 Hour 00



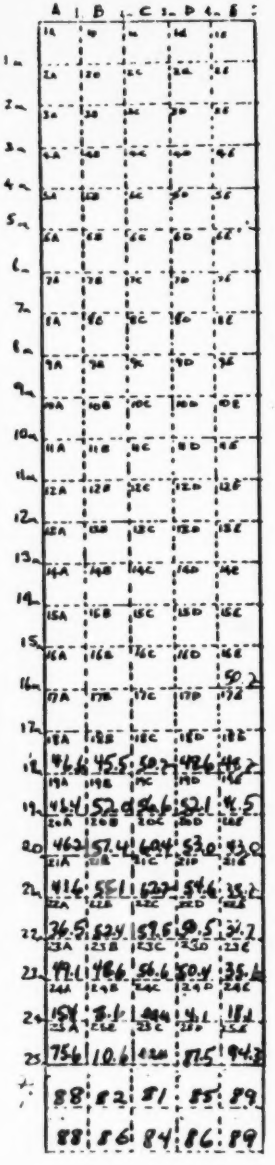
T_2 Hour 28.5



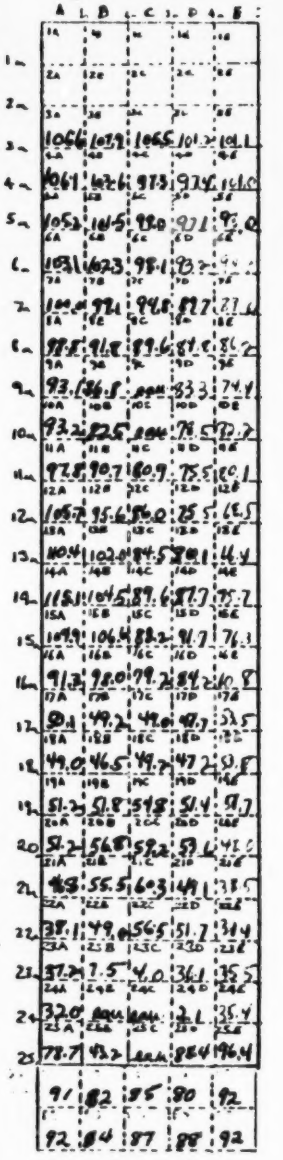
T_3 Hour 47.8

T_4 Hour 69.8

T_5 Hour 74.5



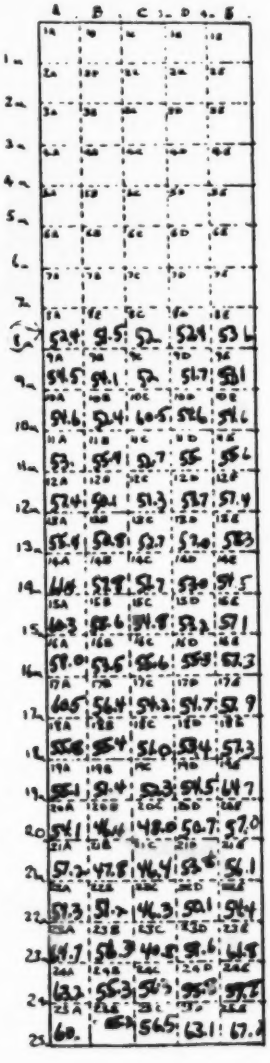
T_6 Hour 93.8



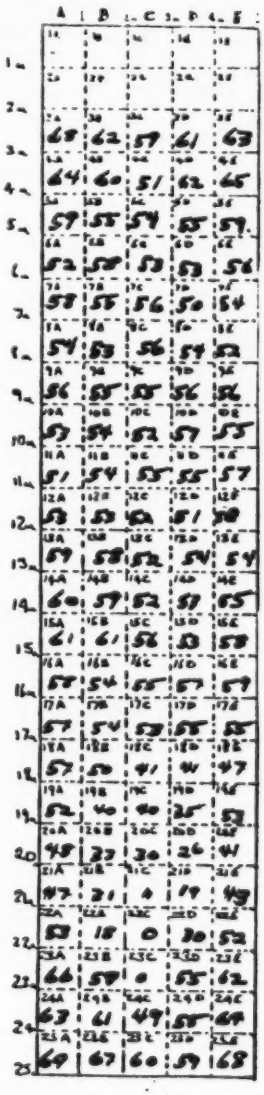
ICE THICKNESS

TEST 010

T_1 Hour 00

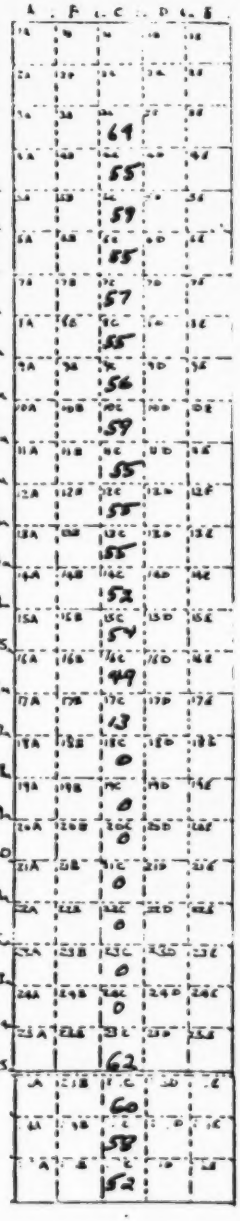


T_2 Hour 19.0



T_3 Hour 24.0

T_4 Hour 67.9



ice thickness in mm
1 meter grid

POOR
QUALITY
ORIGINAL